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Reinforced concrete tank walls and bridge abutments: Early-age behaviour, analytic approaches and numerical models

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ABSTRACT

The problem of early age cracking is still underestimated in concrete structures in which limited possibility of deformation under thermal-moisture effects may generate dangerous stresses. Thermal-shrinkage cracking of externally-restrained concrete members is frequently observed in wall members supported on previously cast foundation, such as tank walls, bridge abutments or retaining walls.

The article discusses early-age behaviour of reinforced concrete tank walls and bridge abutments. The character of thermal and shrinkage stresses along with typical cracking patterns are presented. Several examples of real structures in which early age cracking was observed are also shown in the article. Finally, available analytic and numerical models to predict thermal-shrinkage stress development and cracking risk in early age concrete in such structures are discussed. An example of numerical analysis is presented to show the advantage of the numerical approach of analysis.

1. Introduction

The phenomenon of early age thermal-shrinkage cracking is known in massive concrete structures such as dams or thick foundation slabs. The main cause of these cracks is inhomogeneous volume changes connected with thermal and moisture gradients occurring in concrete structures due to the hydration process. Due to exothermic nature of cement hydration significant temperature develops in early age concrete structures. In structural members with thin sections the generated heat dissipates quickly and causes no problem. Inside thicker sections the conditions are close to adiabatic and maximum temperature can reach even 50–70 °C [1–4]. Furthermore, the internal temperature decreases slowly while the surfaces in direct contact with environment cool rapidly. As a result, thermal gradients occur across the section of concrete members. One of the causes of high temperature increase and its non-uniform distribution between surface layers and inner parts of massive concrete member is low thermal conductivity of concrete which slows down the natural cooling process. Simultaneously, during hydration of concrete shrinkage deformations occur as a result of chemical reaction of cement and water and moisture exchange with the environment.

The volume changes due to the temperature and moisture variations cause the stresses to arise in a concrete member. These stresses can be defined as self-induced stresses – they are related to internal restraints of the structure, resulting from non-uniform volume changes in a cross-section size. In internally-restrained members during the phase of temperature increase tensile stresses develop in surface layers of the member and compressive stresses are observed inside the member. Inversion of stresses occurs during the cooling phase: inside we observe tensile stresses and in the surface layers – compressive stresses. The self-induced stresses can be expected within e.g. thick foundation slabs, thick walls, dams and each member with the internal temperature considerably greater than the surface temperature. In such members, usually described as massive structures, random crack maps on the surfaces can be observed. It should be also mentioned that the temperature exceeding 65–70 °C which may develop in these massive structures can lead to the delayed ettringite formation (DEF) and consequently to possible damage of concrete [5].

A concrete member can be additionally externally restrained. For example, such a restraint exists along the contact surface of new and mature concrete. As a result, the forced stresses caused by the limited freedom of deformation of the structure are also induced. The forced stresses are often observed in medium-thick members such as reinforced concrete walls. The external restraint can be in a form of an end restraint, when the wall is cast between two previously made concrete members, or a continuous edge restraint, when the wall is cast against an old set foundation. Very

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Nomenclature

T	temperature, K
T_i	initial temperature of concrete, K
T_a	ambient temperature, K
$\dot{T} = \frac{\partial T}{\partial t}$	time derivative of temperature
c	moisture concentration, kg/kg
c_i	initial moisture concentration, kg/kg
$\dot{c} = \frac{\partial c}{\partial t}$	time derivative of moisture concentration
$W = \frac{\rho c}{\rho'_w}$	volumetric moisture, m^3/m^3
$\rho'_w = \frac{m_w}{V_w}$	density of water, kg/m^3
ρ	density of concrete, kg/m^3
m_w	mass of water in concrete, kg
V_w	volume of water in concrete, m^3
c_b	specific heat of concrete, kJ/kg K
$\alpha_{TT} = \frac{\lambda}{c_b \rho}$	coefficient of thermal diffusion, m^2/s
α_{TW}	coefficient representing the influence of the moisture concentration on the heat transfer, m^2 K/s
α_{WT}	thermal coefficient of moisture diffusion, m^2/s K
α_{WW}	coefficient of moisture diffusion, m^2/s
K	coefficient of the water-cement proportionality, which described amount of waterbounded by cement during the hydration process with the rate of heat generated per unit volume of concrete, m^3/J
q_v	rate of heat generated per unit volume of concrete, W/m^3
α_p	thermal transfer coefficient, W/m^2 K
β_p	moisture transfer coefficient, m/s
α_T	coefficient of thermal deformability
α_W	coefficient of moisture deformability
$C(t, \tau)$	the creep function, expressing the creep strains in time t, generated by the elementary stress applied in time τ
$F()$	the function describing the boundary (failure) surface
$f()$	the function describing the yield surface
s_m	the non-dimensional co-ordinate, $s_m = \sigma_m/f_c$
t_e	the equivalent age of concrete
t_o	the non-dimensional co-ordinate, $t_o = \tau_{okt}/f_c$
τ	the age of concrete subjected to the loads
τ_{okt}	the octahedral stress
σ_m	the normal mean stress

often the external restraint is a combination of these two forms. In these cases a series of vertical cracks starting from the base are usually observed [6–8]. It should be also pointed out that the stresses resulting from the external restraint add to the effects of the internal restraint [9].

The magnitude of thermal-shrinkage tensile stresses generated in a concrete member during hardening depends on many technological and material factors such as: concrete mix proportions and type of concrete components; conditions during concreting and curing of concrete, such as initial temperature of concrete, kind of formwork, the use of insulation or pipe cooling; technology of concreting, such as segmental concreting; boundary conditions, such as ambient temperature, temperature of neighbouring members, wind, humidity [5,10]. The other important factors are the dimensions, geometry and support conditions limiting the freedom of deformation of the concrete member subjected to changes in volume [11].

The problem of high temperature developing during hardening of concrete and consequent non-uniform volumetric changes and stresses arising in concrete structures are well-known in engineering practice. Specifications typically limit the maximum temperature to 65 °C and the maximum temperature difference between the inner and the outer part of a concrete structure to 15–20 °C [1–4] as it is believed that concrete can withstand strains caused by such temperature differences. Thus, it is necessary to control the temperature and moisture changes in the structure. Appropriate technology of concreting, curing conditions and fresh concrete mix proportions must be ensured to provide that and minimise the risk of cracking.

The article concentrates on the early-age behaviour of externally-restrained structures such as reinforced concrete tank walls and bridge abutments. The character of thermal and shrinkage stresses and typical cracking patterns observed in these structures are presented. Examples of real reinforced concrete tank walls and bridge abutments in which early age cracking was observed are also shown in the article. Available analytic models as well as the numerical model developed by the authors to predict thermal-shrinkage stress development and cracking risk in early age concrete in such structures are outlined in the article. Finally, the possibilities of the proposed numerical model are presented on the example of the real tank wall with diagnosed early age cracking.

2. Problem overview

Most commonly construction of tank walls and bridge abutments begins with casting of a foundation proceeded with concreting of the rest of the structure in a form of a wall. At the moment of the wall construction concrete of the foundation is cooled down and a part of shrinkage deformations has occurred.

The early age wall is subjected to substantial self-heating (Fig. 1a) which yields the possibility that significant thermal strains occur in the member. Displacement of the wall with respect to the foundation is limited by the bond developing between the two and transverse reinforcement located in that joint. In the first period of the bond development compression in the wall occurs as a result of its thermal expansion (Fig. 1b). This happens usually during the first 1–3 days. Then the wall starts to cool down due to the heat transfer to environment, which takes another few days. During this period, the development of tensile stresses in the wall is observed (Fig. 1b) because of a huge restraint exerted by the previously cast foundation (full bonding in the joint between two concretes is formed at that moment). At the same time moisture removal from the wall occurs (Fig. 1c) which adds to the tensile stresses during the whole process (Fig. 1d). The loss of moisture from concrete is caused both by evaporation at the surface of the wall and internal drying due to the water being consumed during the hydration process.

Fig. 1 presents general development in time of temperature, humidity and induced thermal-shrinkage stresses in the discussed walls. In fact, the values of generated temperature and the loss of moisture differ in each point of the wall according to the temperature and moisture exchange with environment. Consequently, the values of generated stresses vary in particular areas of the wall due to different thermal and shrinkage strains as well as due to different degree of restraint of the wall by the foundation. Nevertheless, the main character of their development presented in Fig. 1 is valid in most areas of the wall. The described thermal-shrinkage stresses in externally restrained walls result from a coupled action of self-induced and restraint stresses.