Tunnelling and Underground Space Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Effect of fibres on early age cracking of concrete tunnel lining. Part II: Numerical simulations

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ARTICLE INFO

Article history:
Received 18 February 2015
Received in revised form 29 April 2016
Accepted 31 July 2016
Available online xxxx

Keywords:
Shrinkage
Cracking
Ring tests simulations
Fibre-reinforced concrete
Concrete tunnel lining

ABSTRACT

The early-age cracking of concrete structures increases permeability and diffusivity and moreover accelerates the penetration of liquid, gas and aggressive agents. Consequently, the serviceability of these structures could be reduced drastically. Early-age cracking might be due to external loading, but also to the internal or external restraint resulting from autogenous, drying and thermal shrinkage. This study focuses more specifically on these latter phenomena.

In the first part of this study (see effect of fibres on early-age cracking of concrete tunnel lining - Part I: Laboratory testing), ring tests were performed to investigate the sensitivity of concrete to cracking due to both shrinkage strain and type of fibre (two organic fibres and one steel fibre were studied).

Ring test results were then used to validate the capacity of a chemo-thermo-viscoelastic damage model aimed at reproducing the complex behaviour of fibre-reinforced concrete subjected to restrained shrinkage through identifying the material parameters with standardised tests. The numerical simulations conducted on a real tunnel lining show that for the studied geometries and concrete mixtures, thermal shrinkage constitutes the major phenomenon capable of causing early-age transverse cracks and moreover crack opening is highly dependent on the type of reinforcement. Modifications to both fibre type and lining thickness may serve to avoid the onset of transverse cracks.

1. Introduction

Early-age cracking may occur in massive concrete structures due to strains generated by internal and external restraints. The chemical reactions between cement and water are exothermic and result in thermal dilatation followed by thermal shrinkage (temperature may exceed 60 °C in massive concrete structures). Moreover, during hydration reactions, capillary pressures are induced by water consumption and external drying. Consequently, autogenous and drying shrinkage occurs. Regardless of their origin, when autogenous, thermal and/or drying strains are restrained due to boundary conditions and gradients, stresses are generated (Gawin et al., 2006; Benboudjema and Torrenti, 2008; Azenha et al., 2009; Briffaut et al., 2011; Klemczak and Knoppik-Wróbel, 2015; El Bitouri et al., 2016). In the case of external restraint (foundations, rock formation for tunnels, a cold joint), the maximum concrete tensile strength may be reached, thus causing transverse cracks to appear. In addition, temperature and relative humidity gradients increase during hydration and drying, which in turn leads to self-equilibrated stresses and concrete skin cracking. The serviceability of massive structures, such as tanks, bridges, nuclear containment and tunnels, may be reduced due to the penetration of aggressive agents like carbon dioxide, sulphate and chloride ions. Moreover, cracking may induce a significant increase in concrete permeability and become responsible for water inflows in the tunnel when no seal has been installed behind the concrete lining (according to the RATP,[1] 40% of Paris subway stations are subjected to this phenomenon). For this particular construction method, a thick lining is supposed to ensure sealing of the structure.

To avoid cracking or at least limit crack opening, the tunnel lining could be reinforced by a welded steel mesh with a limited structural role. Nevertheless, positioning this reinforcement is a time-consuming process and the concrete cover may not fulfil its function, thus leading to disorders associated with early corrosion.

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http://dx.doi.org/10.1016/j.tust.2016.08.001
0886-7798/

Please cite this article in press as: Briffaut, M., et al. Effect of fibres on early age cracking of concrete tunnel lining. Part II: Numerical simulations. Tunnel. Underg. Space Technol. (2016), http://dx.doi.org/10.1016/j.tust.2016.08.001

Companies responsible for tunnel projects are therefore interested in substituting a fibre reinforcement (either metal or polypropylene) for this welded anti-crack mesh, while keeping in mind that polypropylene microfibres also prevent concrete from spalling in the case of fire. For hardened concrete, the use of macrofibres in concrete tunnel lining for the purpose of replacing structural reinforcements has already been studied (Nanakorn and Horii, 1996; Buratti et al., 2011, 2013; Chiaia et al., 2009).

The objective of this study is to investigate the effect of fibres on early-age cracking, more specifically the cracking due to thermal shrinkage. No individual study has in fact been found in the literature by the authors, whereas drying and autogenous shrinkage restraints have been widely investigated, especially on shotcrete (e.g. Malmgren et al., 2005; Ansell, 2010; Bryne et al., 2014a).

In the second part, numerical simulations will be performed in order to study the impact of fibres on the shrinkage cracking of a concrete tunnel lining. The chemo-thermo-mechanical analysis of the behaviour of concrete at early ages has been investigated in-depth on simple structures based on either empirical formulae (Xiang et al., 2005; Jeon et al., 2008) or a viscoelastic damage model (Benboudjema and Torrenti, 2008; Briffaut et al., 2011; Buffo-Lacarriere et al., 2011). However, studies focusing on the effect of both fibres and structural geometry (in the case of tunnel lining) are still lacking. After a short description of the model used in this study, the material parameters will be identified on experimental results, presented in the part I. The ring test will then be introduced to validate the ability of the model to reproduce the early-age behaviour of FRC. Lastly, drying, thermal and mechanical simulations of the concrete lining of an actual tunnel will be presented, by highlighting the influence of each phenomenon (thermal, autogenous and drying shrinkage) and then describing in greater detail the influence of both fibres and cross-section thickness.

2. Numerical modelling of the frc behaviour

2.1. Thermo-hydro-chemo-mechanical modelling

At early age, several phenomena occur simultaneously. These phenomena must be taken into account in order to provide a relevant analysis of the thermal active ring test results and highlight the effect of fibres. The thermo-hydro-chemo-mechanical model used is a viscoelastic model with coupling between creep and damage. It has been described in further detail in de Sa et al. (2008), Benboudjema and Torrenti (2008) and Briffaut et al. (2011). Only the main features of this numerical model will be provided hereafter.

The evolution of hydration is successfully modelled by introducing a chemical affinity (Ulm and Coussy, 1998) and then considering that the chemical reactions are thermo-activated according to Arrhenius' Law (Regourd and Gauthier, 1980). The temperature evolution is derived by the energy balance equation, which includes the heat release due to hydration reactions, as well as by assuming that the thermal boundary conditions are convective. Since drying is very slow (up to 10^6 times slower than heat transfer), no coupling between hydration and drying has been considered.

The autogenous shrinkage strain and thermal strain (respectively ε_{au} and ε_{th}) are assumed to evolve linearly with the degree of hydration (Ulm and Coussy, 1998; Mounanga et al., 2006) and with the coefficient of thermal expansion considered as a constant (Laplante and Boulay, 1994). The drying shrinkage strain (ε_{ds}) is calculated using the approach proposed in Baroghel-Bouny et al. (1999), which is based on the mechanics of porous media. Drying creep strain ε_{dc} is modelled using the approach proposed by Bažant and Chern (1985). During hydration, the mechanical behaviour of concrete is modelled by an isotropic elastic damage model coupled with creep. Such a set-up proves to be sufficient for predicting cracking due to restrained strain (De Sa et al., 2008; Briffaut et al., 2011) since the stresses generated are mainly tensile ones. Both Young's modulus E and tensile strength f_t evolve with increases in the degree of hydration (De Schutter, 1999), leading to a continuously increasing tensile strain threshold with hydration (Benboudjema and Torrenti, 2008).

The relationship between apparent stresses $\boldsymbol{\sigma}$, effective stresses $\tilde{\boldsymbol{\sigma}}$, damage D, elastic stiffness tensor $\mathbf{E}$, elastic strains $\boldsymbol{\varepsilon}_e$, basic creep strains $\boldsymbol{\varepsilon}_{bc}$ (see thereafter), total strains $\boldsymbol{\varepsilon}$ and previously defined strains is expressed as follows:

$$\begin{aligned}\boldsymbol{\sigma} &= (1-D)\tilde{\boldsymbol{\sigma}} = (1-D)\mathbf{E}(\xi)\dot{\boldsymbol{\varepsilon}}_e \\ &= (1-D)\mathbf{E}(\xi)(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_{bc} - \dot{\boldsymbol{\varepsilon}}_{au} - \dot{\boldsymbol{\varepsilon}}_{th})\end{aligned} \tag{1}$$

where D is given by the following law inspired by Mazars' proposal (Mazars, 1986):

$$D = 1 - \frac{\kappa_0}{\hat{\varepsilon}}\left[(1+A_t)\exp(-B_t\hat{\varepsilon}) - A_t\exp(-2B_t\hat{\varepsilon})\right] \tag{2}$$

where A_t (set equal to 1) and B_t are material parameters that control the softening branch of the stress-strain curve in tension. Strain softening induces inherent mesh dependence and leads to failure without any energy dissipation (Pijaudier-Cabot and Bažant, 1987). In order to dissipate the same amount of energy after mesh refinement, when strains have localised in a row of finite elements, a characteristic length l_c relative to mesh size is introduced (Rots, 1988; Cervera and Chiumenti, 2006). The fracture energy also depends on the degree of hydration (De Schutter and Taerwe, 1997).

Lastly, the evolution of B_t parameter with respect to the degree of hydration is expressed as:

$$B_t(\xi) = \frac{(1+A_t/2)}{\frac{G_{ft}(\xi)}{l_c f_t(\xi)} - \frac{f_t(\xi)}{2E(\xi)}} \tag{3}$$

where ξ is the degree of hydration, l_c the characteristic length of the finite element, f_t the tensile strength, E the Young's modulus, and G_{ft} the fracture energy.

High stress levels or post-peak loading lead to nonlinear creep strains in both compression and tension (which may induce failure). According to Mazzotti and Savoia (2003), creep strains ε_{bc} are partially included in the expression of the equivalent strain defined by Mazars (1986).

To reproduce the reversible component of basic creep without increasing the number of model parameters, Kelvin-Voigt units are used (see, for instance, Benboudjema and Torrenti, 2008). The stiffness parameter for each unit is calculated with the equation proposed by De Schutter (1999) and slightly modified thereafter (Benboudjema and Torrenti, 2008) to take temperature effects into account (Ladaoui et al., 2012). According to Bažant and Prasannan (1989), the characteristic time of each chain should not be a parameter defining the evolution laws of creep strains. They proposed a ratio of 10 between the characteristic times of two consecutive chains, which enables avoiding the risk of solving an ill-conditioned problem. To retrieve irreversible creep strains after unloading, an ageing dashpot placed in series with the Kelvin-Voigt chains has also been employed to model basic creep (Briffaut et al., 2012).

2.2. Simulation of thermal active ring test results

A global strategy has been implemented to identify and validate the entire set of parameters. Standardised tests, such as semi-adiabatic tests, compressive tests, splitting tests and autogenous shrinkage tests, make it possible to identify some of the key model

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