Construction and Building Materials 153 (2017) 55–68

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental and numerical study of effective thermal conductivity of cracked concrete

Lei Shen [a,b], Qingwen Ren [c,*], Linfei Zhang [a], Yan Han [c], Gianluca Cusatis [b]

[a] Hohai University, Hydraulic Structure, Nanjing 210098, China
[b] Northwestern University, Civil and Environmental Engineering Department, Evanston 60208, USA
[c] Hohai University, Engineering Mechanics, Nanjing 210098, China

HIGHLIGHTS

- Simulations show concrete thermal conductivity has a decrease of 20–30% during tensile and compressive failure.
- Debonding of aggregate and mortar dominants the reduction of concrete thermal conductivity.
- Experiments show a 25% decrease in thermal conductivity during compressive test.
- Wang Jiajun model is calibrated to calculate the thermal conductivity of cracked concrete.

ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form 4 June 2017
Accepted 4 July 2017
Available online 15 July 2017

Keywords:
Cracked concrete
Effective thermal conductivity
Mini-scale modeling
Finite element method
Experiment
Wang Jiajun model

ABSTRACT

The pronounced decrease of Effective Thermal Conductivity (ETC) due to the cracking behavior of concrete changes the temperature profile in concrete structures, indirectly inducing the redistribution of thermal stresses. To study this phenomenon, a mini-scale numerical method within the framework of finite element method is proposed for both tensile and compressive cracked concrete and this method is applied to obtain quantitative relationships between tensile or compressive strain and ETC. Results show that (a) for tensile dominated failure, concrete ETC decreases by 23% during the plastic stage whereas little decrease is found at complete failure; (b) for compressive dominated failure, ETC decreases by 30% during the plastic stage, and then becomes stable afterwards. In the softening stage ETC linearly decreases with the increase of compressive strain; (c) it is the interfacial thermal resistances induced by the micro-cracks between aggregates and mortar rather than the macro-cracks that play the dominant role in this phenomenon; (d) concrete ETC becomes anisotropic when cracks appear. The experiments show that compressive cracked concrete's ETC vertical to cracks dramatically decreases by 20–25% at plastic drop stage and then becomes stable at the plastic steady stage. The numerical results are used to determine the interfacial thermal resistance factor in Wang Jiajun model. The proposed formulation provides results that are in excellent agreement with experiments.

1. Introduction

It is acknowledged that cracking behavior in massive concrete structure is inescapable, especially for hydraulic engineering and nuclear reactor structures [1]. Many researchers put their efforts on the influence of cracks on the safety and water retaining performance of dams while little attention has been paid so far to the effects of cracks on temperature distribution. Thermal loads induced by hydration reaction of cement paste and cold weather as well are a common reason for cracking in hydraulic structures [2]. Hence it is of vital importance to study the cracks' influence on the thermal distribution in the massive concrete structure.

According to Fourier's Law and energy conservation law, the accuracy of numerical studies primarily relies on two input thermal parameters, i.e., thermal conductivity and specific heat capacity. However, recent experimental investigations [3–5] showed that, after the occurrence of concrete cracking, specific heat capacity was proved to remain unchanged, while the thermal conductivity decreased significantly. Therefore studying the evolution of thermal conductivity during concrete failure is the main objective of this study.

Numerical investigations in recent years have increased the understanding of this topic. Tang et al. [6] found out by using the

---

* Corresponding author.
E-mail address: renqw@hhu.edu.cn (Q. Ren).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.038

RFPA2D program [7,8] that for uniaxial compression tests the maximum drop of effective thermal conductivity (ETC) of a concrete specimen was 24% during softening. In their finite element method (FEM) based program, the elements' thermal conductivity was set to zero when the compressive or tensile stress reached the peak value. Obviously, this assumption did not correctly reflect the thermal behavior inside cracks. Hence Shen et al. [9] proposed a mini-scale numerical method to simulate the thermal conductivity of tensile cracked concrete. In this work, the heat bridge effect, caused by the higher conductivity of aggregates, and the interfacial thermal resistance effect, induced by the rupture of aggregates and mortar were emphasized to be the main mechanism of the remarkable drop of conductivity (23%) during the plastic stage. Wu et al. [10] also found the debonding of aggregate and mortar would lead to a temperature jump across the micro-cracks at Interfacial Transition Zone (ITZ). Therefore numerical study on this topic should be carried out at mini scale in order to capture the debonding phenomenon of aggregate and mortar.

Numerical simulations, coupled with experiment, are considered to be an effective and efficient tool for successfully examining material properties. Hence experimental investigations are necessary. Vejmelkova et al.'s [4] experiment showed up to 40% decrease in thermal conductivity in cracked concrete specimens which were heated up to 600 °C to impose randomly distributed cracks. Perkowski [11] analyzed the variation of thermal conductivity due to brittle damage in concrete subjected to the ultimate compression load and observed an average of 20% decrease in thermal conductivity for high-performance concrete specimens. The aforementioned experiments have two shortcomings: one is that the thermal conductivity evolution could not be obtained, and another one is that measurements of conductivity are taken place after unloading when cracks undergo unloading and closure.

In the current study, three-dimensional simulations of heat transfer at mini scale and experiments of compressive cracked concrete ETC are carried out. Then a semi-theory model is calibrated by numerical results and compared to experimental data.

2. Numerical method and results

Concrete has a highly heterogeneous microstructure and its composite behavior is exceedingly complex. Therefore, reliable predictions of the behavior of the material based exclusively on experimental studies have become limited. For obtaining a deeper understanding, FEM-based simulations at mini scale have been employed to study the macroscopic constitutive mechanical [12] and thermal behavior of concrete [13] and their coupling mechanism [7–9].

At mini scale, concrete is considered as a three-phase composite material consisting of mortar matrix, aggregate, and ITZ. Material properties of different phases are directly assigned to the elements in order to characterize the random heterogeneity in concrete numerically. The ability of this numerical approach has been validated by good agreements between experimental data and numerical results [9,10,14,15]. One point should be highlighted that some authors use the term "meso-scale" (no ITZ) in a wider sense to include the "mini-scale" [16–19] (see Fig. 1).

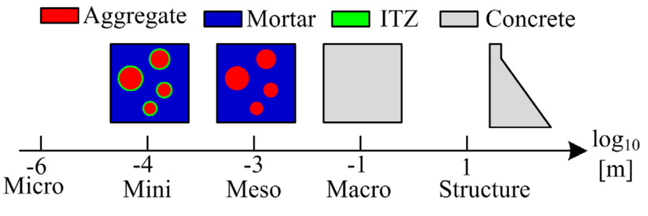

Fig. 1. Illustration of concrete material at multi scale.

2.1. Mini-scale numerical method

The first step is to obtain the crack information of concrete during low friction uniaxial tension and compression tests. The three phases, namely mortar, aggregate and ITZ, are simulated by concrete damage plastic (CDP) model with different parameters given in Section 2.2. The constitutive is basically introduced in Section 2.1.1 which is provided by commercial finite element software ABAQUS [20].

Secondly, thermal conductivity of each element is modified with respect to its cracking opening which is obtained from the first step. The details of thermal behavior in crack are discussed and the modifier formulas for three cracked phases are assumed in Section 2.1.2.

The last step is to calculate the macroscopic ETC of concrete specimen with modified thermal conductivity distribution. The homogenization method is proposed in Section 2.1.3. By repeating these three steps above, one can obtain the evolution of ETC during tensile and compressive failure.

2.1.1. Concrete damage plastic model

Mechanical behavior of concrete-like material, e.g., cracking in tension and crushing in compression, can be well simulated by using CDP model [14,21,22]. The CDP model was first proposed by Lubliner et al. [23] for monotonic loading, and was further developed by Lee and Fenves [24] to consider the dynamic and cyclic loadings. The basic framework of the CDP model is illustrated as follows.

The uniaxial stress-strain curves can be converted into stress versus plastic strain curves. Tensile damage factor d_t and compressive damage factor d_c are assumed as increasing functions of the equivalent plastic strain ($\tilde{\varepsilon}^{pl}$), $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$ (subscripts, 't' and 'c' stand for tension and compression, respectively). Herein, the degradation of the elastic stiffness is characterized by damage variables, d_t and d_c, and the stress-strain relationships (shown in Fig. 2) under tension and compression are:

$$\begin{aligned} \sigma_t &= (1 - d_t)E_0(\varepsilon - \tilde{\varepsilon}_t^{pl}) \\ \sigma_c &= (1 - d_c)E_0(\varepsilon - \tilde{\varepsilon}_c^{pl}) \end{aligned} \tag{1}$$

respectively, in which E_0 is the initial (undamaged) elastic modulus, σ is stress and ε is strain. The evolution equation of the hardening parameters subjected to multi-axial loading are developed from

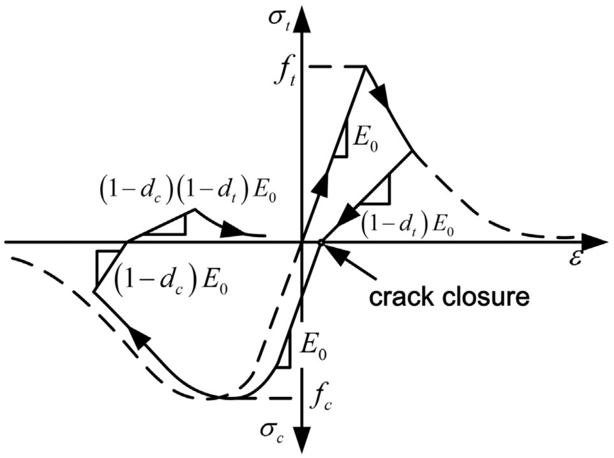

Fig. 2. Unaxial loading path of CDP model. f_c is usually 10 times of f_t.