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Temperature and critical flaw size evolution dependence of fracture strength of the concretes

Ruzhuan Wang[a], Weiguo Li[b]

[a] Chongqing Key Laboratory of Nano–Micro Composite Materials and Devices, School of Metallurgy and Materials Engineering, Chongqing University of Science and Technology, Chongqing 401331, China
[b] College of Aerospace Engineering, Chongqing University, Chongqing 400030, China

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ABSTRACT

The fracture strength of concretes at elevated temperature has attracted increasing attention owing to the great risk of exposing them to elevated temperatures. However, there are few theoretical studies on high temperature fracture strength of the concretes. In this paper, a novel and simple temperature dependent fracture strength model for the concretes was developed by using the Griffith energy method and a concept of energy storage capacity. The effect of critical flaw size evolution is considered by this temperature dependent model based on primary and simple method. It should be noted that this model has no any fitting parameter and can be used simply just with some basic material parameters which have the clear physical meaning. Excellent agreement was achieved between model prediction and experimental measurement.

1. Introduction

Concrete is one of the most important civil engineering materials. The concretes generally have high strength, high durability and high workability. These properties have made the concretes for the widely applications of the fundamental materials of more and more structures and buildings [1–5].

The increasing attention has been drawn to the temperature dependence of fracture behavior of concretes owing to the increased risk of exposing them to elevated temperatures. As showed in experimental measurements, the fracture strength of concretes depends on the temperature [6–10]. For example, Bamonte and Gambarova tested the ratio of fracture strength at a certain temperature to that at room temperature of self-consolidating concrete (SCC) in the temperature range of 20 °C and 600 °C [6]. The ratio of the concrete was reported to decrease from 1 at 20 °C to about 0.34 at 600 °C. Pan et al. tested the strength of ordinary Portland cement (OPC) based concrete and geopolymer concrete at room temperature, 200 °C, 300 °C and 550 °C, respectively [7]. They indicated that geopolymer concrete showed a more significant increase in fracture strength at elevated temperatures compared to OPC based concrete. Sideris tested the ratio of fracture strength at a certain temperature to that at room temperature of SCC at room temperature, 200 °C and 350 °C [9]. Khaliq and Kodur reported the fracture strength of SCC and fiber reinforced SCC in the temperature range of 20–800 °C [10]. The experimental measurements showed that the temperature dependent fracture strength of the concretes were controlled by the microstructures and their evolutions with increase of temperature.

However, the existing temperature dependent experimental measurements are fairly dispersed. In addition, the measurements of temperature dependence of material strength are extremely difficult with highly consumption of an enormous amount of time and resources. In the field of theory, some work reported the temperature dependent fracture strength model for ceramics. Li et al. proposed a theoretical model for the ceramics based on a fracture thought at high temperature [11,12]. Yet they did not consider the effects of microstructures such as critical flaw. The fracture strength of materials is controlled by the critical flaw. As the temperature increases the microstructures changes such as the growth of micro and macro pores or cracks and impurities formation, etc. This should affect the value of critical flaw size. The effects of those factors on the fracture of materials will transit to the effects of flaws on the fracture and the sizes of which are included in the critical flaw size. Wang et al. proposed a theoretical model for the ceramic composites considering effects of temperature and microstructures [13,14]. Yet the derivation process of the model is quite complicated and which has many parameters to be determined, leading to the difficulty in prediction and simulation. Currently, for the concretes there is a knowledge gap on predictive theories at high temperatures. The quantitative relationships for fracture strength and its dependence on critical flaw evolution are particularly barely known. Therefore, developing a rational model for concretes at elevated

E-mail addresses: wrz@cqu.edu.cn (R. Wang), wgli@cqu.edu.cn (W. Li).

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temperature is a major issue that requires more attention by researchers in order to propose a rational theoretical method to analyze experimental under-dispersed data and offer guidelines for experiment and material design.

In this work, a novel and simple temperature dependent fracture strength model for concretes was developed based on the primary and simple method. Good agreement between predicted value and experimental measurement was obtained.

2. Theoretical model

The fracture of brittle materials is a quite complicated process, especially at elevated temperatures. It involves the growth of micro and macro pores or cracks, the interface between two phases, impurities formation and the temperature, etc. Generally, the characterization of effects of microstructures and their evolutions with temperature on the fracture strength of materials is very difficult. There has been no one set theory "set in stone" to handle all of these factors in fracture. A system's thermodynamic state that describes the system's structure can be changed by two methods, one is the applied load, and the other is the thermal heat transfer. Materials are formed when molecular bonds are established to create structures. While breaking up the structures requires severing these molecular bonds either by applied load or by heat transfer. From the viewpoint of the energy, the fracture of brittle materials is a process of energy changes associated with molecular bond breaking between the fractured parts for creating new solid surfaces. The energy is associated with certain kind of movement. For example, kinetic energy is associated with the motion of object and potential energy is associated with the stationary state of the object [15]. According to First Law of Thermodynamics, energy can convert from one form to another. To predict the fracture strength of concretes, the challenge is the danger of them with a large operating temperature range. Under such circumstance, the effect of temperature should be taken into account. As the kinetic energy and potential energy are highly temperature dependent, the fracture strength of concrete should change with increase of temperature. This can also be understood by considering the cleavage of bond as a motion of a particle escaping from energy well. The studies have showed that there exists a maximum storage of energy of brittle materials during fracture [11–14,16], which can be determined by both elastic energy and the quantity equivalent heat energy [11–14]. In this paper, we use the concept of the maximum storage of energy, which includes kinetic energy and potential energy as

$$W_{\mathrm{TOTAL}} = E_{\mathrm{P}}(T) + kE_{\mathrm{K}}(T) \tag{1}$$

where W_{TOTAL} is energy storage capacity unit volume; $E_{\mathrm{P}}(T)$ is temperature dependent potential energy; $E_{\mathrm{K}}(T)$ is kinetic energy unit volume; k is the ratio coefficient between the potential energy and the kinetic energy.

At a certain temperature i.e. isothermal process, the type of potential energy is strain energy. According to the Griffith energy criterion, the change of strain energy of a specimen unit thickness due to the presence of a crack can be calculated from the expression [17]

$$W_{\mathrm{c}} = \frac{-\pi s^2\sigma^2}{E} \tag{2}$$

where s is crack size; E is Young's modulus; σ is applied stress. The strain energy for breaking the bonds per cracking area can be expressed as [18]

$$W_{\sigma} = -\frac{\partial W_{\mathrm{c}}}{\partial(2s)} = \frac{\pi s\sigma^2}{E} \tag{3}$$

As the critical flaw propagates the catastrophic failure of brittle material occurs. The critical flaw is the key control mechanisms of fracture strength of materials. The critical flaw size is a basic material parameter which is related to the microstructures such as grain, pores and the interface conditions. The critical flaw size of materials with a certain microstructure is supposed to be a material constant. For the critical flaw, W_{σ} in Eq. (3) is the critical strain energy release rate; s becomes the critical flaw size and σ is equal to fracture strength of materials. The temperature dependent critical strain energy release rate can be expressed as follows

$$W_{\sigma}(T) = \frac{\pi s(T)\sigma_f(T)^2}{E(T)} \tag{4}$$

In Eq. (4), $\sigma_f(T)$ is the temperature dependent fracture strength of materials; $s(T)$ is the critical flaw size of materials at temperature T; $E(T)$ is the Young's modulus of materials at temperature T. It can be observed that the energy storage capacity associated with fracture can be expressed by the critical flaw size.

From the viewpoint of the above mentioned fracture of molecular bond, we use Eq. (5) to express the kinetic energy of molecules per volume

$$E_{\mathrm{K}}(T) = \frac{3}{2}\beta NT \tag{5}$$

where β is Boltzmann constant; N is the number of the molecules unit volume.

Then the energy storage capacity unit volume can be expressed as

$$W_{\mathrm{TOTAL}} = W_{\sigma}(T) + kE_{\mathrm{K}}(T) = \frac{\pi s(T)\sigma_f(T)^2}{E(T)} + k\frac{3}{2}\beta NT \tag{6}$$

As the temperature increases up to melting point (T_{m})

$$W_{\sigma}(T_{\mathrm{m}}) = 0 \tag{7}$$

Substituting $T = T_0$ and $T = T_{\mathrm{m}}$ into Eq. (6)

$$\frac{\pi s(T_0)\sigma_f(T_0)^2}{E(T_0)} + k\frac{3}{2}\beta NT_0 = k\frac{3}{2}\beta NT_{\mathrm{m}} \tag{8}$$

where T_0 is a reference temperature.

Then the coefficient k can be obtained as

$$k = \frac{2\pi s(T_0)\sigma_f(T_0)^2}{3E(T_0)\beta N(T_{\mathrm{m}}-T_0)} \tag{9}$$

Submitting Eqs. (9) to (6), W_{TOTAL} can be obtained as

$$W_{\mathrm{TOTAL}} = \frac{\pi s(T)\sigma_f(T)^2}{E(T)} + \frac{\pi s(T_0)\sigma_f(T_0)^2}{E(T_0)(T_{\mathrm{m}}-T_0)}T \tag{10}$$

Combining Eqs. (6), (8) and (10), a novel and simple model for predicting temperature and critical flaw size evolution dependence of fracture strength of concretes can be obtained as

$$\sigma_f(T) = \sigma_f(T_0)\left(\frac{s_{\mathrm{c}}(T_0)}{s_{\mathrm{c}}(T)}\frac{E(T)}{E(T_0)}\left(1-\frac{T-T_0}{T_{\mathrm{m}}-T_0}\right)\right)^{1/2} \tag{11}$$

The model can be used to predict temperature dependent fracture strength of concretes with the material parameters such as Young's modulus, critical flaw size and melting point. Each parameter is a basic material parameter and has the clear physical meaning, and which is not hypothetical one. Compared to the destructive tests of temperature dependent fracture strength measurements, those parameters can be achieved much easier from experiments or material handbook. Meanwhile, compared to the reported temperature dependent fracture strength model for ceramic composites having the ability to describe effects of microstructures [14], this novel model is much simpler as only the primary and simple method is used. It should be noted that the model has no fitting parameter, which is an easy-to-use method for the concrete engineering.