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Mesoscale simulation of fatigue behavior of concrete materials damaged by freeze-thaw cycles

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HIGHLIGHTS

- A mesoscale numerical approach is developed for the combined FTC and fatigue problem of concrete.
- The cyclic constitutive laws are proposed in mesoscale for RBSM.
- The static and fatigue behavior with/without FTC damage can be simulated well.
- As FTC damage becomes bigger, the slope of S-N curve also gets steeper.

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ABSTRACT

Frost damage is a common durability problem for concrete structures in cold and wet regions, and in many cases, the frost damage is coupled with fatigue loadings such as the traffic loads on bridge decks or pavements. In this paper, to investigate the basic fatigue behavior of concrete materials affected by frost damage, a mesoscale approach based on Rigid Body Spring Method (RBSM) has been developed, of which the concrete material can be divided into three parts: mortar, coarse aggregate and interfacial transition zone (ITZ) between them. First, the cyclic constitutive laws are developed at normal and shear directions for mortar and ITZ, and verified with the existing experimental data in compression and tension fatigue. Then, several levels of frost damage are introduced by different numbers of freeze-thaw cycles (FTCs), and finally, the static tests and fatigue tests are conducted using the frost damaged concrete. The simulation results on the static strength and fatigue life show a good agreement with experimental data, and found that as the frost damage level (irreversible plastic deformation) increases, not only the static strength, but also the fatigue life at each stress level will decrease. The S-N curves of frost damaged concrete still follow a linear relationship but with bigger slopes, and the frost damaged concrete will become more ductile under fatigue loadings.

1. Introduction

Frost damage mechanism under freezing and thawing cycles (FTCs) is an important issue for service life evaluation of concrete structures in cold regions. Once frost damage happens, deterioration process like chloride ingress, carbonation and even the frost action itself will be largely accelerated, resulting in shorter service life. In addition, the frost action is always coupled with external loads, and the combined effect will also affect the material degradation and structure performance significantly. If the saturation degree exceeds a critical value [1], significant damage in the porous skeleton will occur due to several kinds of pore pressures during ice formation [2–6]. This kind of internal damage will be cumulated with numbers of FTC and result in gradual degradation in material properties [7–8]. For the combined effect of FTC damage and fatigue loads, Hasan et al. [9] conducted the fatigue tests on the concrete specimens which have experienced different numbers of FTCs, and found a serious reduction of the fatigue life in compression. Although the cyclic frost action and fatigue loading have different natures, the damage of both can be reflected by the initiation and propagation of micro cracks, which will finally

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result in the increasing residual deformation, reduction in stiffness and strength, and so on. Therefore, it is possible to model and simulate the combined effects by the same approach.

Many concrete models are either macro model or micro model. The macro models can be directly applied to structural analysis and obtained experimentally without theoretical basis, but with less applicability once the input variables or working conditions become different. The micro models have strong theoretical bases and cover much more influential factors, but may not be convenient to study structural performances due to lack of linkage between micro and macro models. Other than above two approaches, the mesoscale approach is more general and can be applied to various kinds of damages. On one hand, the macro nonlinear mechanical behavior can be simulated by defining the constitutive laws for mortar, coarse aggregate and ITZ in mesoscale. For example, Nagai et al. [10] presented a 2D mesoscale model using RBSM, which can simulate the macroscale nonlinear properties in both compression and tension. The same mesoscale model was also extended to simulate concrete with frost damage [11], and the time-dependent degradation under fatigue loadings [12]. On the other hand, the microscale events in the porous matrix of cement paste can also be up-scaled to the mortar level, such as the pore pressures during FTCs based on poromechanics [13], and the moisture transport and chloride migration [14–15]. Some other mesoscale modeling works for concrete material can be also found [16–17]. Therefore, it would also be beneficial to adopt RBSM in mesoscale for the combined degradation problem of FTC and fatigue loadings.

In this study, based on the mesoscale RBSM, the constitutive laws under cyclic mechanical loadings are developed first, and verified with the fatigue experiments for non-FTC damaged mortar and concrete in both compression and tension. The damage effect by FTCs is also included in the above constitutive laws. For the analysis of combined effect, the FTC tests are simulated first to obtain different levels of frost damage, then using the FTC damaged concrete, static tests are conducted to obtain the residual strengths, and followed by the fatigue simulation based on each residual strength. The results are discussed in detail and compared with experimental data, which are found in a satisfactory agreement.

2. Method of analysis

2.1. Concept of RBSM

The RBSM is a discrete numerical analysis method, which was first developed by Kawai [18]. Unlike the continuum methods such as Finite Element Method or Finite Difference Method, RBSM is a more proper way to simulate splitting and cracking in cement-based materials like mortar and concrete. Also, compared to other discrete method like Distinct Element Method, RBSM is more suitable for small deformation and tiny cracks which are often seen in concrete structures.

The concrete to be simulated is divided into polyhedron elements, and the mesh is arranged randomly using a Voronoi diagram. Each Voronoi cell represents a mortar or aggregate element in the model. For two adjacent elements, there are two springs connecting them: normal spring and shear spring, which are placed at the boundary of the elements (see Fig. 1). Each element has two translational and one rotational degree of freedom at the centroid. The normal and shear stiffness are calculated by assuming a plane stress condition as follows [10]:

$$\begin{aligned} k_n &= E/(1-\nu^2) \\ k_s &= E/(1+\nu) \end{aligned} \tag{1}$$

where k_n and k_s are the stiffness of normal and shear spring; E and ν are the elastic modulus and Poisson's ratio of the element (either mortar or aggregate), respectively. In case of the springs on the mortar-aggregate interface, the stiffness is given as a weighted average of mortar and aggregate element:

$$\begin{aligned} k_n &= (k_{n1}h_1 + k_{n2}h_2)/(h_1 + h_2) \\ k_s &= (k_{s1}h_1 + k_{s2}h_2)/(h_1 + h_2) \end{aligned} \tag{2}$$

where the subscripts 1 and 2 represent the mortar and aggregate elements respectively, and h is the length of the perpendicular line from the centroid of element to the boundary. The stress-strain relationship of the normal spring will adopt a linear tension-softening curve, and a normal distribution was assumed for the tensile strength to increase the heterogeneous performance as [10]:

$$\begin{aligned} f(f_t) &= \tfrac{1}{\sqrt{2\pi}s}\exp\left[-\tfrac{(f_t-\mu)^2}{2s^2}\right] \\ s &= -0.2\mu + 1.5 \end{aligned} \tag{3}$$

where f_t is the tensile strength of the element, and for $f_t < 0$, set $f_t = 0$; μ is the average value of f_t; and s is the standard derivation. For the shear spring of porous body, the following criterion is adopted [10]:

$$\tau_{\max} = \pm(0.11{f_t}^3(-\sigma + f_t)^{0.6} + f_t) \quad (\sigma \leqslant f_t) \tag{4}$$

where σ is the normal stress. And for the interface between mortar and aggregate, the shear spring criterion is as follows:

$$\tau_{\max} = \pm(-\sigma\tan\varphi + c_i) \tag{5}$$

where φ and c_i are constant values. For the shear springs of both mortar and ITZ, the ideal plastic performance is assumed when the local shear strain is small [10], however, if the shear sliding becomes so big that the attached length of two elements is significantly reduced, the shear transfer will also decrease linearly as:

$$\begin{aligned} \tau'_{\max} &= \tau_{\max}(1 - \delta_s/l_{elem}) \\ k_s' &= k_s(1 - \delta_s/l_{elem}) \end{aligned} \tag{6}$$

where δ_s is the sliding distance and l_{elem} is the length of boundary between two elements. It can be imaged that the local shear strain in mesoscale could be several orders larger than the averaged shear strain in macroscale when failure happens, thus the above formulation can still guarantee a shear softening behavior in macroscale.

The tensile cracking and shear sliding will also interact with each other for both mortar elements and ITZ. The concept of mesoscale analysis is that the constitutive laws should be as simple as possible to simulate the complicated macroscale mechanical behavior. Considering that the tension stress transfer capability may be reduced with damage induced by sliding at the same location, the tension softening stress is assumed reducing linearly with the amount of shear sliding between two adjacent elements:

$$\begin{aligned} f_t' &= f_t(1 - \delta_s/l_{elem}) \\ k_n' &= k_n(1 - \delta_s/l_{elem}) \end{aligned} \tag{7}$$

Similarly, the shear strength ($\tau''_{\max}$) and stiffness (k_s'') also can be affected by the tensile cracking, and a linear relation is assumed:

$$\begin{aligned} \tau''_{\max} &= \tau'_{\max}(1 - w/w_{\max}) \\ k_s'' &= k_s'(1 - w/w_{\max}) \end{aligned} \tag{8}$$

where w is the crack width in normal direction and $w_{\max}$ is the maximum crack width which tensile and shear transfer can happen. The above coupling effect has been verified by the uniaxial compression tests and biaxial compression-tension tests [10]. The mathematical solution of the RSBM is briefly summarized in Appendix A.