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MODELING FREEZE AND THAW DAMAGE IN CONCRETE DECKS USING DAMAGE MECHANICS

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Research has documented that freeze-thaw cycles (FTCs) deteriorate mechanical properties of concrete such as strength and stiffness. This paper presents a general approach to model the changes in these mechanical properties. It also presents a generalized bounding surface approach, where limit surface is allowed to collapse inward and form a new failure surface (residual strength) corresponding to the number of FTCs. Within this formulation, softening equations for strength reduction and the increase in ultimate strain of concrete under FTCs are proposed. Stress-strain curves are obtained and the anisotropic degradation in mechanical properties is captured. The results show a good correlation with experimental data available in the literature.

Keywords: Bounding surface, Stress-strain curves, Anisotropic damage.

1 INTRODUCTION

Concrete is a composite material widely used in various types of infrastructures such as buildings, pavements, dams, etc. These infrastructures are exposed to different environmental conditions during their lifetime with significant effects on their mechanical properties. Freeze-thaw process is one of the conditions that deteriorates the internal structure of concrete by inducing microcracks. As a result, it affects the strength, stiffness, and deformation capacity of concrete. Experimental data (Shang and Song 2006, Hasan *et al*. 2008) show that the strength of concrete decreases as the number of freeze-thaw cycles (FTCs) increases. Moreover, Hasan *et al.* (2008) have argued that concrete becomes more flexible under loading after the application of FTCs.

Detwiler *et al*. (2007) have reported that freeze-thaw damage occurs in the concrete in the form of microcracks. The freeze-thaw damage is caused by hydraulic pressure due to frozen water expansion in the concrete voids. If enough space is not provided for the extra volume of frozen water, new cracks nucleate or the existing cracks propagate. Repeating this process will result in loss of strength and stiffness. Therefore, it is clear that a meaningful constitutive model is needed to capture these changes in the concrete. This paper presents a model based on damage mechanics to address the influence of freeze-thaw process on concrete.

2 GENERAL FORMULATION

The general formulation presented here follows the basic principles of mechanics and thermodynamics. Guided by the work of Ortiz (1985) and Yazdani (1993) for small deformations, the general form of the damage surface is given as:

$$\Psi(\boldsymbol{\sigma},k) = \frac{1}{2}\boldsymbol{\sigma}:\boldsymbol{R}:\boldsymbol{\sigma} - \frac{1}{2}t^2(\boldsymbol{\sigma},k) = 0 \tag{1}$$

where **σ** is the stress tensor, k is a scalar-damage parameter, **R** represents the response tensor used to specify the directions of induced damage, and the symbol **":"** represents a tensor-contraction operation. The damage function is given by t(**σ**,k) serving as a hardening-softening function for the damage surface. The condition $\Psi(\boldsymbol{\sigma},k) < 0$ represents an elastic domain, and the condition $\Psi(\boldsymbol{\sigma},k) > 0$ is not allowed for rate-independent processes. A class of constitutive model that is considered appropriate for brittle solids such as concrete is given as:

$$\boldsymbol{\varepsilon} = \boldsymbol{C}(k):\boldsymbol{\sigma} \tag{2}$$

where **ε** represents strain tensor. The compliance tensor **C**(k), is assumed to take an additive decomposition form of $\mathbf{C}(k) = \mathbf{C}^0 + \mathbf{C}^c(k)$, where $\mathbf{C}^0$ is the initial undamaged compliance tensor of the material, and $\mathbf{C}^c$ is the added flexibility tensor associated with the accumulation of damage. Because of nonlinearity of constitutive relations caused by damage, the rate form of the flexibility tensor is considered as:

$$\dot{\boldsymbol{C}}(k) = \dot{\boldsymbol{C}}^c(k) = \dot{k}\boldsymbol{R} \tag{3}$$

Guided by experimental data, the damage function is postulated by Ortiz (1985) as follows:

$$t(\boldsymbol{\sigma},k) = f_c e \frac{\ln(1+E_0 k)}{(1+E_0 k)} \tag{4}$$

where f_c is the strength of concrete under uniaxial compression, E_0 is the initial Young's modulus, and *e* represents the natural number. To progress further, specific form of the response tensor **R** must be stated. Shang and Song (2006) have argued that FTCs make no changes on the failure mode of concrete. In this paper only the compression mode of damage is considered. The damage mode is identified by response tensor **R** given as:

$$\boldsymbol{R} = \frac{\boldsymbol{\sigma}^- \otimes \boldsymbol{\sigma}^-}{\boldsymbol{\sigma}^- : \boldsymbol{\sigma}^-} + \alpha H(-\lambda)(\boldsymbol{I} - \boldsymbol{i} \otimes \boldsymbol{i}) \tag{5}$$

where "⊗" is the tensor product operator, $\boldsymbol{\sigma}^-$ represents the negative cone of the stress tensor, $H(-\lambda)$ is defined as the Heaviside function of the maximum eigenvalue of $\boldsymbol{\sigma}^-$, and **I** and **i** are the fourth and second order identity tensors, respectively. $\boldsymbol{\sigma}^-$ is a stress tensor incorporating only the negative eigenvalue of **σ**.

3 BOUNDING SURFACE AND SOFTENING FUNCTIONS

The concept of bounding surface theory and its application to fatigue processes proposed by Wen *et al.* (2012). In this research, as shown in Figure 1, limit surface (LS) represents the ultimate strength of the concrete under various load paths when the number of FTCs is zero. As the number of FTCs increases, the strength of the material is expected to decrease, represented by the inward collapse of the LS. Collapsing of the LS creates new residual strength surfaces (RS) depending on the number of FTCs.

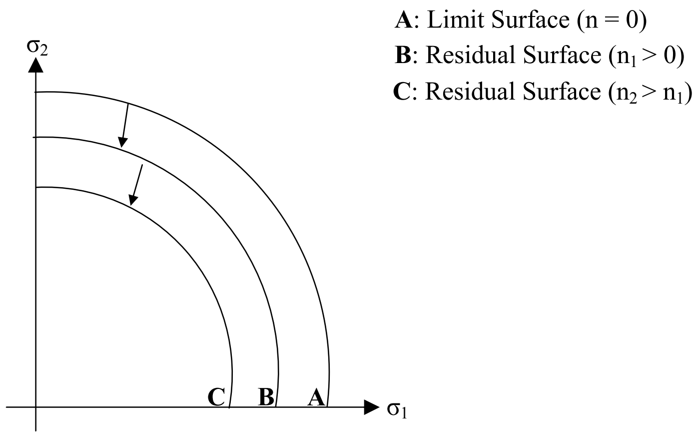

Figure 1. Schematic representation of bounding surface approach in biaxial strength space.

In order to incorporate the effects of the freeze-thaw damage into the model, $F_\sigma(n)$ function is added to the damage function t(**σ**,k):

$$t(\boldsymbol{\sigma}, k(n)) = F_\sigma(n).F(\boldsymbol{\sigma}, k) \tag{6}$$

where $F_\sigma(n)$ is designated as the softening function due to FTCs, and F(**σ**,k) is the strength function associated with monotonic loading. $F_\sigma(n)$ must be formulated in a way that the original formulation is retained when FTC is zero.

By considering experimental data provided by Shang and Song (2006), it can be inferred that the changes of concrete strength are linear with respect to numbers of FTCs. In addition, it also can be seen that strength reduction is path-dependent. Guided by the experimental data, the softening function is proposed as:

$$F_\sigma(n) = \frac{\sigma}{f_c} = 1 - B\left[\frac{\boldsymbol{\sigma}:\boldsymbol{\sigma}}{tr^2(\boldsymbol{\sigma})}\right]^C n \tag{7}$$

where B and C are material parameters. These material parameters can be obtained by utilizing two uniaxial and biaxial compression tests after FTCs, respectively.

To predict the behavior of concrete under FTCs, its deformational characteristics need to be investigated as well. A schematic stress-strain behavior of concrete under FTCs is illustrated in Figure 2. It shows the reduction of strength and subsequently the increase in strain for a given FTC. The experimental works done by Shang and Song (2006) and Hasan *et al.* (2008) also demonstrate that the ultimate strain of concrete increases with FTCs. It could be seen that like strength, increase in strain is a function of number of FTCs as well as load paths.

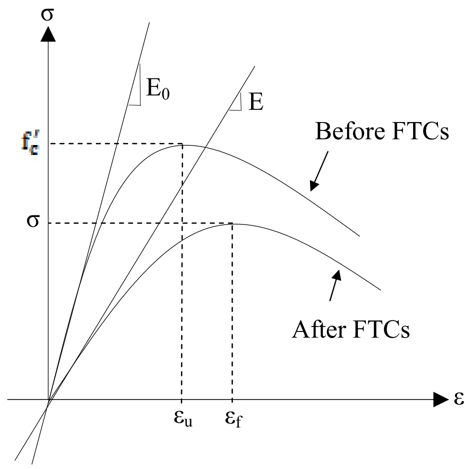

Figure 2. Schematic representation of stress-strain curves before and after FTCs application.

Based on the discussion above, the softening function for ultimate strain can be postulated as:

$$F_\varepsilon(n) = \frac{\varepsilon_f}{\varepsilon_u} = 1 + H\left[\frac{\sigma:\sigma}{tr^2(\sigma)}\right]^Q n \tag{8}$$

where ε_f is the ultimate strain after FTCs, ε_u is the monotonic ultimate strain, and H and Q are material parameters. H and Q are obtained by utilizing uniaxial and biaxial compression test after a specified number of FTCs, respectively.

4 SIMULATION AND DISCUSSION

In this section, the model predictions for various load paths and FTCs are illustrated and the results are compared to the published experimental work of Shang and Song (2006). The discussion of the results is offered for the examples given. One should note that the aim of any constitutive modeling at the material level should be to predict the overall response of materials rather than to replicate the experimental data.

Figure 3 illustrates the model prediction of the residual strengths of concrete under different number of FTCs in biaxial strength space. The outermost curve represents the limit surface corresponding to the quasi-static strength of the material prior to freeze-thaw damage. As freeze thaw damage occurs, the limit surface is allowed to shrink as demonstrated in Figure 3. Experimental data are also plotted for comparison to theoretical results and for different cycles of freeze and thaw. The agreement with experimental data is quite satisfactory considering the simplicity of the relations used.

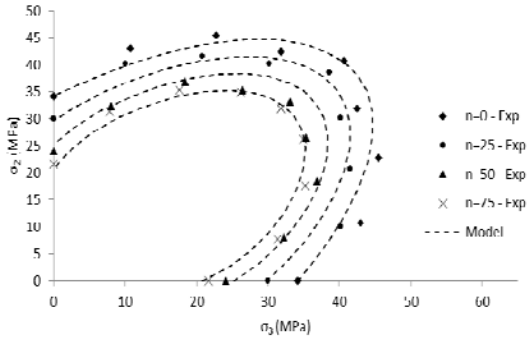

Figure 3. Residual strength surfaces for various numbers of FTCs in biaxial strength space.

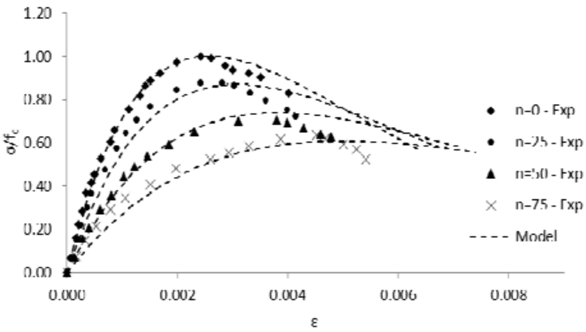

Figure 4. Stress-strain curves under uniaxial compression after various numbers of FTCs.

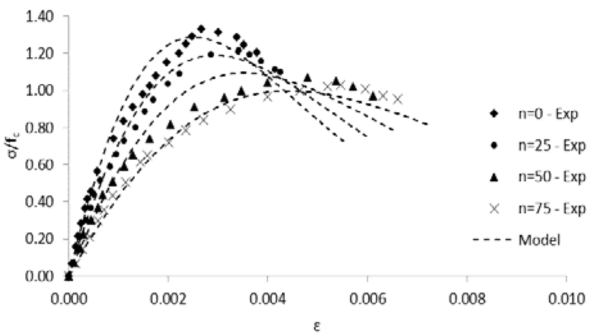

Figure 5. Stress-strain curves under biaxial compression with stress ratio of 0.5 after various numbers of FTCs.

Figures 4 and 5 show the effectiveness of the constitutive model in predicting the stress-strain curves of concrete for various load paths under different numbers of FTCs. Both curves show clear reduction in strength and increase in strains with increasing number of freeze-thaw cycles. Experimental data are also provided for comparison. The salient features of the nonlinear behavior are captured by the proposed theory.

5 CONCLUSION

In this paper the effect of freeze-thaw damage on concrete behavior was modeled using damage mechanics and the bounding-surface approach. The limit surface was allowed to contract based on the number of freeze-thaw cycles. This was accomplished by postulating a softening function that was linear in relation to number of cycles while being stress-path dependent. The model was finally compared with experimental data and showed a satisfactory correlation.

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