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Constitutive model of concrete damaged by freeze–thaw action for evaluation of structural performance of RC elements

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HIGHLIGHTS

- The effects of FTC on concrete behavior are included in the damage model.
- The FTD model considers separately the effect of FTC on compressive and tensile strength.
- A new relationship to properly evaluate the equivalent number of FTC is proposed.
- Different experimental and numerical results are compared.
- An experimental campaign on simply supported beams subjected to FTC is simulated.

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ABSTRACT

The coupled environmental-mechanical damage model extended by the authors to include the degradation effects on structural behavior of RC structures due to freezing-and-thawing cycles (FTC) is reformulated and generalized in the present work in order to better simulate the different aspects of the physical phenomenon. In particular the model is modified to consider separately the effect of FTC respectively on compressive and tensile strength and a new relationship to properly evaluate the equivalent number of FTC is proposed. To validate the model, an experimental campaign carried out on simply supported beams subjected to FTC is simulated. By comparing obtained numerical results with experimental evidence, the model is proved to be suitably accurate in reproducing the main aspects observed during tests: failure load, ultimate displacement, and failure mode. Actually the enhancement of freeze and thaw – mechanical model gives the base for the definition of a reliable numerical tool for analysis of RC structures subjected to FTC.

1. Introduction

Durability of RC constructions gained increasing interest during last decades and, especially in countries with cold climate, freezing-and-thawing cycles (FTC) represent one of the most dangerous phenomena for RC structures. Indeed a high number of RC constructions are built in wet environments, such as bridge piers, bridge slabs, off-shore platforms, etc. making FTC a serious problem for their durability. Moreover in many cases interaction between different mechanisms takes place: for instance in bridge slabs surface cracking and/or scaling due to FTC accelerates carbon dioxide, chloride, and oxygen diffusion processes which may induce reinforcement corrosion.

The problem of FTC has been studied since the middle of the last century from the material point of view. Although different questions remain unanswered, nowadays the main mechanisms that lead to degradation due to FTC have been identified and just about clarified (e.g. [1,2]). This has permitted to define guidelines, codes and rules for the design of concrete resistant to FTC. On the other hand there are existing RC structures that have not been designed to be frost-resistant and their safety level need to be assessed. To this aim, appropriate constitutive models for concrete subjected to the action of FTC are needed. However most of the studies published in literature on concrete behavior under FTC primarily focus only on the degradation of concrete properties, while few researches have been carried out on testing and modeling the stress–strain relationships of concrete undergoing repeated cycles of freeze–thaw [3].

It is widely accepted that two different types of frost damage can be distinguished (e.g. [2]): internal damage and surface scaling. The latter is generally caused by freezing of concrete when its sur-

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face stays in contact with weak saline solution and its main effects are the reduction of concrete cover and of anchorage capacity leaving the inner concrete substantially undamaged. On the other hand internal damage is mainly caused by freezing of water within concrete's pore system. It affects compressive strength and peak strain at maximum compression (e.g. [2,4–6]), elastic modulus (e.g. [2,4–6]), tensile strength (e.g. [4,6]), fracture energy (e.g. [6]) and anchorage capacity (e.g. [6]).

Some researchers investigated the degradation of compressive and tensile strength due to frost degradation. Shang and Song [4] performed compression tests and direct tension tests on concrete cubes under different number of FTC in order to measure strength reduction with increasing number of FTC. Duan et al. [5] studied the behavior of prisms with different concrete compositions under uniaxial compression and investigated the effect of FTC on confined concrete specimens. Hanjari et al. [6] performed compression tests and splitting tests on concrete specimens, while Hassanzadeh and Fagerlund [7] and Fagerlund [8] evaluated reduction of compressive strength and tensile strength after the application of a particular frost-degradation procedure.

It is worth noting that very little attention has been devoted to studying structural performance of RC elements subjected to FTC. For instance Hassanzadeh and Fagerlund [7] studied a series of RC beams with different geometry and reinforcement ratio subjected to frost degradation. From this study they concluded that frost degradation leads to reduction of load carrying capacity and ductility; they also observed a change of failure mode from ductile (due to yielding of steel) to brittle (due to crushing of concrete in compression zone).

In this work an innovative coupled environmental-mechanical damage model proposed by the authors in [9–11] is reformulated and extended in order to better simulate the different aspects of the FTC physical phenomenon. A number of experimental campaigns on different concrete grades under various freeze–thaw conditions are considered, also in case of applied tensile load. The model is thus enriched in order to capture the main effects of FTC on material characteristics. In particular the enhanced model demonstrates to be able to properly account for reduction of both compressive and tensile strength, increasing of peak strain and reduction of elastic modulus.

In the first part of the paper the coupled environmental-mechanical constitutive damage model is briefly recalled and extended by introducing two different environmental damage variables, i.e. the positive and the negative ones, in order to properly reproduce the different effects of the environmental attack on compressive and tensile behavior. Then the new freeze and thaw degradation (FTD) model is proposed, from the general formulation up to the parameters definition, taking advantage of a number of experimental works available in literature. In particular, different validation examples are considered in order to show the suitability of the model in reproducing the main effects of frost degradation on concrete properties. Finally eight beams tested by Hassanzadeh and Fagerlund [7] are simulated and the capability of the FTD model in capturing the observed experimental behavior of structural elements is proved.

2. Theoretical framework for coupled concrete damage model

In the present section the coupled damage model developed by the authors for concrete is briefly recalled. Readers can refer to [9–11] for a more detailed description of the original formulation.

The constitutive model is formulated within the framework of continuum damage mechanics. It is based on an isotropic plastic-damage model with two distinct damage scalar variables: one for tension and one for compression (e.g. [9–14]). The model is able to represent the stiffness degradation, the hardening and softening behavior and the stiffness recovery with load reversals due to the closure of cracks, making it suitable for cyclic and dynamic analyses.

The constitutive law is described by the following equation:

$$\boldsymbol{\sigma} = (1-d^+)\bar{\boldsymbol{\sigma}}^+ + (1-d^-)\bar{\boldsymbol{\sigma}}^- \tag{1}$$

where $\boldsymbol{\sigma}$ is the usual Cauchy stress tensor, $\bar{\boldsymbol{\sigma}}^+$ and $\bar{\boldsymbol{\sigma}}^-$ are the positive and negative parts of the effective stress tensor obtained via a spectral decomposition. The effective stress tensor is defined as:

$$\bar{\boldsymbol{\sigma}} = \mathbf{C}_0 : \boldsymbol{\varepsilon}^e \tag{2}$$

with $\mathbf{C}_0$ the fourth-order elastic stiffness tensor and ε^e the elastic part of the total strain tensor, which is split in an elastic and plastic part.

According to [9] the following damage criterion is adopted:

$$g = \left(\frac{\bar{\tau}^+}{r^+}\right)^2 + \left(\frac{\bar{\tau}^-}{r^-}\right)^2 - 1 \le 0 \tag{3}$$

where r^+ and r^- denote respectively positive and negative threshold monitoring the size of expanding damage surface and $\bar{\tau}^+$ and $\bar{\tau}^-$ are the equivalent stresses defined as following:

$$\begin{aligned} \bar{\tau}^+ &= \sqrt{E\bar{\boldsymbol{\sigma}}^+ : \mathbf{C}_0^{-1} : \bar{\boldsymbol{\sigma}}^+} \\ \bar{\tau}^- &= \sqrt{\sqrt{3}\,(K\bar{\boldsymbol{\sigma}}_{oct}^- + \bar{\boldsymbol{\tau}}_{oct}^-)} \end{aligned} \tag{4}$$

with E the concrete Young modulus; $\boldsymbol{\sigma}_{oct}$ and $\boldsymbol{\tau}_{oct}$ the octahedral normal and shear stresses respectively, and the scalar K a material property that accounts for the increase of compressive strength due to biaxial compression. In particular K depends on the ratio R_0 between 2D and 1D compressive strengths according to:

$$K = \sqrt{2}\,\frac{1-R_0}{1-2R_0} \tag{5}$$

The adopted evolution laws for damage variables are:

$$\begin{aligned} d^+ &= 1 - \tfrac{r_0^+}{r^+}\exp\left[A^+\left(1-\tfrac{r^+}{r_0^+}\right)\right] \\ d^- &= 1 - \sqrt{\tfrac{r_0^-}{r^-}}(1-A^-) - A^-\exp\left[B^-\left(1-\sqrt{\tfrac{r^-}{r_0^-}}\right)\right] \end{aligned} \tag{6}$$

where r_0^+ and r_0^- describe the initial threshold variables, r^+ and r^- are the current threshold variables and A^+, A^- and B^- are model parameters.

Extending previous works (e.g. [9,13,14]), the coupling between environmental degradation and mechanical behavior is obtained defining two different scalar damage variables, d_{env}^+ and d_{env}^-, which affect respectively the positive and negative part of the effective stress tensor according to the following relationship:

$$\begin{aligned} \boldsymbol{\sigma} &= (1-d_{env}^+)(1-d^+)\bar{\boldsymbol{\sigma}}^+ + (1-d_{env}^-)(1-d^-)\bar{\boldsymbol{\sigma}}^- \\ &= (1-d^{*+})\bar{\boldsymbol{\sigma}}^+ + (1-d^{*-})\bar{\boldsymbol{\sigma}}^- \end{aligned} \tag{7}$$

where d^{*+} and d^{*-} are respectively the positive and negative coupled damage variables. Independently from their specific definition, the environmental damage variables are represented by an increasing function with time, which means $\dot{d}_{env}^+ \ge 0$ and $\dot{d}_{env}^- \ge 0$. The introduction of two environmental damage variables, respectively the positive and the negative ones, allows to represent in an independent way the effects of attack in tension and in compression, both in terms of stiffness and strength reduction, Fig. 1, in agreement with experimental evidences for example in case of frost degradation.

Finally the model assumes that the damage criterion also describes the plastic surface so that the development of material damage is simultaneous with the accumulation of irreversible strains according to the following relation:

$$\dot{\boldsymbol{\varepsilon}}^p = \beta E H(\dot{d})\,\frac{\langle\bar{\boldsymbol{\sigma}} : \dot{\boldsymbol{\varepsilon}}\rangle}{\bar{\boldsymbol{\sigma}} : \bar{\boldsymbol{\sigma}}}\,\mathbf{C}_0^{-1} : \bar{\boldsymbol{\sigma}} \tag{8}$$