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Structural nominal concrete strength derived by statistical mechanics

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HIGHLIGHTS

- Concrete behaviour was derived by a damage model based on statistical mechanics.
- The model gives a nonadditive entropy for small concrete structures.
- The derived nominal concrete strength decreases as the structural size increases.
- A lower size effect is highlighted for lower temperatures.
- It was shown that the size effect vanishes at absolute zero.

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ABSTRACT

The purpose of this paper is to model the effects of the structural size and temperature on the nominal strength of concrete structures.

Based on thermodynamics of irreversible processes, concrete damage theory and statistical mechanics, a constitutive behaviour of concrete was first derived. Then, generalized Boltzmann entropy was calculated by using the number of failure surfaces defined in the concrete microstructure. The number of states is defined as the number of possible failure surfaces. It was shown that states are correlated. This gives a nonadditive entropy for small structures. A theoretical nominal strength taking into account the structural size and temperature effects was deduced.

Thereafter, a one parameter rigid failure mechanism was considered to model experimental tests performed on concrete structures. The theoretical approach was applied to experimental tests performed on notched beams. A lower size effect is highlighted for lower temperatures. Theoretical results were compared with experimental test results performed on notched beams under bending. Comparison showed a good agreement.
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Notations

An over single bar denotes a vector and two over bars denote a second order tensor.

1. Introduction

Concrete behaviour varies with the size and temperature of a loaded structure. The size effect in solid mechanics is the structural size d effect on the nominal strength σ_N, when geometrically similar structures having different sizes are considered. The experimental nominal strength of structures scaled in three dimensions is defined by Eq. (1) as proposed

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by Bazant [1].

$$\sigma_N = c_N \frac{F_{\text{exp}}}{d^2} \tag{1}$$

where F_{exp} is the experimental peak load and c_N is a constant. Quasi-static experimental tests performed on concrete beams under bending show that the experimental nominal tensile strength decreases as the structural size increases [1–5]. Plastic limit analysis and elasticity theories ignore size effects, even though these effects are important for the structural design [1].

Experimental tests performed on concrete specimens show a temperature dependence of the experimental nominal strength. Isotherm experimental tests performed by Maturana et al. [4] on notched concrete beams at temperatures ranging from −170 to 20 °C showed that the nominal tensile strength decreases as the temperature increases. Furthermore, to measure compressive and tensile strengths of concrete, Shoukry et al. [6] conducted tests at temperatures ranging from −20 to 30 °C. These tests showed a linear decreasing of the nominal strength as temperature increases.

Experimental tests performed on notched beams show that failure is the result of microcracking in a fracture process zone whose size is related to the size of aggregates. The size of this process zone is constant, whereas, the size of the structure may be changed [1,3].

Size effect law (Bazant [1])

Bazant [1] proposed a law for the nominal tensile strength bridging limit analysis for small structures and linear elastic fracture mechanics (LEFM) for large structures (Fig. 1). The proposed size effect law (SEL) should be applied to structures where a crack already exists. The nominal tensile strength is given by Eq. (2).

$$\sigma_N = \sigma_c \left(1 + \frac{d}{d_a \lambda}\right)^{-1/2} \tag{2}$$

where σ_c is tensile strength for very small structures, denoted also $\sigma_c = Bf_t$, where B is a constant and f_t is a tensile strength of the material obtained from a standard test, d_a is the average aggregate size and λ is a constant.

Multi-fractal scaling law (Carpinteri et al. [2])

Multi-fractal scaling law (MFSL) proposed by Carpinteri et al. [2] predicts a structural size effect. The nominal tensile strength is given by Eq. (3).

$$\sigma_N = f_\infty \left(1 + \alpha \frac{d_a}{d}\right)^{1/2} \tag{3}$$

where α is a constant. The MFSL gives a constant tensile strength for large structures. This corresponds to a zero slope in the bi-logarithmic strength versus size diagram. On the other hand, the SEL (Eq. (1)) gives a slope $-\frac{1}{2}$ in agreement with LEFM.

Carpinteri et al. [2] describe a transition from disorder for small scales to order for large scales. MFSL can be related to a concept of entropy, viewed as a tendency to move towards disorder.

Continuous damage model (Mazars et al. [3])

Among the various scalar damage models, Mazars's one [3] is perhaps the most popular due to its simplicity. Damage represents micro-cracks and voids observed in the material. Damage variable denoted D varies from 0 for a non loaded state to 1 at failure. The Helmholtz free energy of the material per unit volume is given by Eq. (4).

$$\psi = \frac{1}{2}(1 - D)\overline{\overline{\varepsilon}} : \overline{\overline{\overline{\overline{\Lambda}}}} : \overline{\overline{\varepsilon}} + \varphi(T) \tag{4}$$

where $\overline{\overline{\varepsilon}}$ is the elastic strain tensor, $\overline{\overline{\overline{\overline{\Lambda}}}}$ is the fourth order elastic stiffness tensor and φ is a function of temperature T.

In the framework of the continuous damage model, the next hypotheses were assumed:

(1) Free energy, internal energy and entropy are assumed additive and extensive.
(2) Entropy per unit volume ($s = -\frac{\partial \psi}{\partial T}$) is independent of damage.
(3) Constitutive behaviour is derived by thermodynamics of irreversible processes and Clausius–Duhem inequality.
(4) A fixed strain threshold is assumed as an intensive property of the material.

As presented in Ref. [3], the size effect is not predicted by the continuous damage model.

Non local damage model (Mazars et al. [3])

The non local damage model provides a prediction of the size effect. An equivalent strain threshold depending upon the structural size is empirically introduced.

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