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Deterministic size effect in concrete structures with account for chemo-mechanical loading

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ABSTRACT

The work presented here is focused on examining the size effect in concrete structures subjected to different loading conditions, which include a chemo-mechanical interaction. The study involves extensive three dimensional finite element simulations, which incorporate a constitutive law with embedded discontinuity for tracing the propagation of damage pattern. The analysis deals with various mechanical scenarios that incorporate both a cohesive and frictional damage mechanism, as well as the effects of degradation of concrete triggered by continuing alkali-silica reaction (ASR). In the latter case, a chemo-plasticity framework is employed. The first set of simulations provides a deterministic assessment of the size effect in a series of three-point bending tests as well as compression tests. For continuing ASR, it is demonstrated that, by increasing the size of the structure, a spontaneous failure may occur under a sustained load. The numerical examples given here clearly show that the size effect is associated with propagation of localized damage whose rate is controlled by a suitably defined 'characteristic length'.

1. Introduction

The term 'size effect' refers to variation of the nominal strength with size in geometrically similar structures. In general, for the quasi-brittle materials, such as concrete and/or rocks, it has been shown that the ultimate strength of a structure is significantly reduced by increasing its size [1]. In addition, in small structures the response is more ductile than in larger ones. The brittleness is not only affected by the size, but also the actual geometry of the structure, the presence of pre-existing fractures (e.g., notches) and the fracture energy that controls the stress redistribution.

The size effect has been documented experimentally as early as 1921 in the work of Griffith [2] which dealt with assessment of nominal strength of glass fibers. Soon after, the statistical theories began to emerge, which attributed the size effect to the randomness of material strength within the considered domain [3–5]. This approach was dominant until mid-1970s when the deterministic frameworks started to appear. It was then demonstrated that the major cause of the size effect is the stable propagation of damage. A historical overview of different theories is provided, for example, by Bazant and Planas in their monograph [6]. Most of the research has been conducted in relation to quasi-brittle materials, in particular on concrete subjected to tensile damage. Two types of structures were examined, i.e. with and without a pre-existing fracture, such as an initial notch [6]. Several noteworthy studies in this respect have been conducted by Bazant and his co-workers who developed a general energetic-statistical size effect theory for concrete structures [5–8]. The size effect phenomenon is not limited to tensile regime. Cusatis and Bazant [9], for example, investigated the behavior of concrete columns with and without notch under compression; however, in this case the variation of nominal strength with the size of the structure was not very significant. In addition, a number of experimental studies have been performed on the evaluation of size effect in reinforced concrete structures [10,11].

One of the important loading scenarios that has not been considered so far in the assessment of size effect, is the degradation of concrete triggered by chemo-mechanical interaction. An example here is the alkali-silica reaction (ASR). This reaction occurs in concrete structures which are exposed to high humidity environment, such as dams, piers and bridges. The thermodynamic aspects dealing with the chemical sequence and the rate of kinetics of ASR have been discussed, for example, in Refs. [12,13]. At the same time, the effects of chemo-mechanical interaction have also been extensively studied, both experimentally [14] and numerically at a meso as well as macroscale [13,15–17]. The primary objective of this work is to examine the size effect in a broad range of loading conditions that also include damage due to continuing ASR. It is clearly demonstrated that the size effect is associated

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with formation of discrete macrocrcaks and that the mathematical description of propagation process requires the notion of a 'characteristic length'. It is noted that this parameter was employed in the past research, but its definition remains rather ambiguous. In different works, it was loosely interpreted as the 'size of material inhomogeneities' or that of 'the fracture process zone'; i.e. no precise quantitative meaning was assigned. Here, following earlier work reported in Refs. [18–20], the propagation of damage is described in terms of an embedded discontinuity approach, which incorporates volume averaging in order to generate representative homogenized stiffness moduli. In this approach the characteristic dimension is explicitly defined as the ratio of the area of macrocrack to the selected reference volume, the latter identified with that of a finite element containing the discontinuity. Thus, for a fixed FE mesh, if the size of the structure increases, the 'characteristic length' within the elements containing discontinuity changes, which in turn affects the rate of damage propagation and, thus, the nominal strength of the structure.

The outline of this paper is as follows. In the next section, a brief overview of the notion of deterministic size effects is provided. Later, the mathematical formulation of the problem is outlined. This includes the description of both homogeneous and localized deformation, the latter associated with the presence of discrete macrocracks. In the follow up section, the results of numerical simulations are presented. Those comprise a deterministic assessment of the size effect in a series of three-point bending tests as well as compression tests. For continuing ASR, it is demonstrated that, by increasing the size of the structure, a spontaneous failure can occur under a sustained load below the nominal failure value.

2. Size effect in concrete

The existing analytical expressions which quantify the deterministic size effect have been developed for quasi-brittle materials [21,22]. They deal with geometrically similar structures, with or without large pre-existing fractures/notches, and provide an assessment of nominal strength as a function of the characteristic size of the structure. The most commonly used formulae are those developed by Bazant and co-workers (cf. Ref. [6]) based on their extensive research on this topic. In general, the nominal strength is said to be bound for small sizes by the plasticity limit, whereas for large sizes by the approximation based on linear elastic fracture mechanics. The proposed analytical expressions take the form

$$\sigma_N = \begin{cases} f_r^{\infty}\left(1 + r\frac{D_b}{D+l_p}\right)^{1/r} & \text{Type 1 (un-notched structure)} \\ \frac{Bf_t}{\sqrt{1+\frac{D}{D_b}}} & \text{Type 2 (notched structure)} \end{cases} \tag{1}$$

Here, σ_N is the nominal strength, D is the characteristic dimension of the structure, while f_r^{∞} represents the strength corresponding to elastic-brittle material for the case when $D \to \infty$. The remaining constants are largely semi-empirical. The parameters r and l_p control the curvature of the plot and the transition to perfectly plastic response (for $D \to 0$), respectively, while D_b is said to be a 'characteristic length' associated with the thickness of the fracture zone. In the second equation, f_t denotes the tensile strength and B is, again, a geometry-dependent empirical parameter. A schematic representation of these two size effect laws in an affined logarithmic space is depicted in Fig. 1.

It appears that the practical applicability of the existing analytical approximations, such as Eq. (1), is rather limited. Firstly, several of the parameters employed are semi-empirical and there is no systematic procedure for their identification. Even the notion of the 'characteristic length' has a certain degree of ambiguity as it is not precisely defined. Furthermore, the nominal strength of a structure is affected by its geometry, boundary conditions and the strength/deformation properties of the material. Thus, even for simple geometrically similar structures, the last two features may quite significantly impact the strength. Besides, the assessment of maximum nominal strength, which is identified with plastic limit, is questionable, as evidenced by examples provided later in this paper. Also, for very small sizes (i.e. $D \to 0$), the use of a continuum formulation is rather obscure as the concept of REV is no longer applicable. Therefore, it does not seem feasible to establish a unique analytical 'size effect formula' with reliable predictive abilities. To compound the problem, the extrapolation from the existing formulae to more complex geometries than those employed in their development and/or to structures with no geometric similarities is even more problematic.

Given the comments above, it seems that the most reliable approach is an adequate experimental and/or numerical assessment. In fact, the design of complex engineering structures (dams, bridges, powerhouses, etc.) usually requires a numerical analysis. In this case, the notion of size effect is naturally addressed within the analysis itself (i.e., the problem employs the actual geometry and boundary conditions), provided that an adequate procedure for describing the damage propagation is employed. In what follows, the mathematical framework implemented in this work is briefly outlined. Later, the results of numerical simulations are presented addressing a broad range of loading conditions and their impact on ultimate strength in relation to the size of the structure.

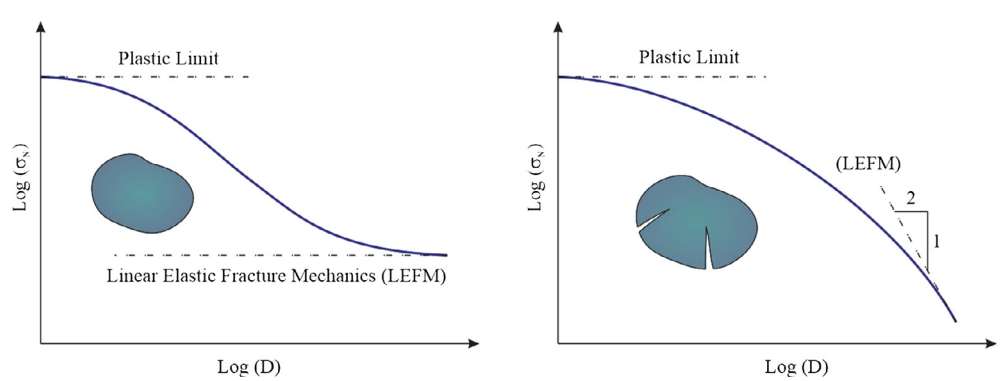

Fig. 1. Size effect law for (a) un-notched structure and (b) structure with initial crack(s).