International Journal of Impact Engineering 38 (2011) 162–170

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Strain-rate effects on concrete behavior

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A R T I C L E I N F O

Article history:
Received 28 August 2009
Received in revised form
25 October 2010
Accepted 25 October 2010
Available online 11 November 2010

Keywords:
Concrete
Lattice models
Strain-rate effect
Creep
Concrete strength

A B S T R A C T

In this paper, a previously developed meso-scale model for concrete, called the Confinement Shear Lattice (CSL) model, is extended in order to include the effect of loading rate on concrete strength and fracturing behavior. The rate dependence of concrete behavior is assumed to be caused by two different physical mechanisms. The first is a dependence of the fracture process on the rate of crack opening, and the second is the viscoelastic deformation of the intact (unfractured) cement paste. In this study, the first mechanism is described by the activation energy theory applied to the ruptures occurring along the crack surfaces, whereas the second mechanism is modeled by the Microprestress–Solidification theory. The developed model is calibrated and validated on the basis of experimental data gathered from the literature.

1. Introduction

Failure and fracturing behavior of concrete are very often treated as time-independent phenomena. This approach, however, is acceptable only as an approximation. In reality, the time dependence is negligible only in a certain range of load duration referred to as short term (or quasi-static) and pertaining to usual material testing lasting a few minutes. On the contrary, it is important for dynamic (impact) loading lasting a few milliseconds and for long-term (sustained) loading lasting for many years.

Under impact loading the influence of the loading rate on concrete behavior becomes an important parameter that must be taken into account in order to have reasonable results. It is generally reported that when the strain rate increases, the ultimate stress (strength), the elastic (secant) modulus, and the peak strain increase (see, among many others, Refs. [1,2]). Under sustained loading, on the other hand, viscoelastic deformations (creep) develop even at constant load and failure can occur at stress levels below the usual quasi-static strength [3].

To simulate correctly the dynamic and viscoelastic response of concrete structures with the inclusion of strain-rate effect, it is essential to adopt a computational model that simulates reliably the transition between diffuse damage, crack initiation, and crack propagation. Such a complex scenario is strongly influenced by concrete heterogeneity and it calls for the adoption of a meso-scale model in which heterogeneity is explicitly simulated.

Many meso-scale models can be found in the literature for the simulation of concrete behavior and, in particular, for the simulation of fracture propagation. Each of them has its own advantages and disadvantages. In the studies of Roelfstra et al. [4], Wittmann et al. [5] and, more recently, Carol et al. [6], concrete is modeled as a three-phase material (aggregate inclusions, mortar matrix, and interface between them), each phase being discretized through finite elements with appropriate material properties. These models describe with great accuracy the interaction between matrix and inclusions, but are almost prohibitive from a computational point of view. Lattice and particle models use a different approach in which the continuum is replaced by a system of discrete elements (rigid particles, truss members, beam members, etc.). Noteworthy examples of lattice and particle models can be found in Refs. [7–13]. These models can handle well the displacement discontinuity associated with fracture and they have been very successful in simulating tensile crack initiation and propagation in concrete.

In this study, a meso-scale model of concrete previously developed by the author is adopted and extended to include strain-rate effects. This model, called the Confinement–Shear Lattice model [14], is able to simulate tensile fracture as well as damage in compression and it has been extensively calibrated and validated in the quasi-static regime [15–17]. The quasi-static formulation of this model is highlighted in the next section.

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0734-743X/$ – see front matter
doi:10.1016/j.ijimpeng.2010.10.030

2. Review of the Confinement–Shear Lattice (CSL) model

The Confinement–Shear Lattice (CSL) model is a meso-scale model simulating the mechanical interaction among coarse aggregate pieces in concrete. The geometry of the model is obtained from the basic properties of the mix-design. Given the aggregate–cement ratio, a/c, the cement content, c, the sieve curve, and a certain volume of material, V, the number n_i of aggregate pieces whose characteristic size lies in a specified size interval of average size D_i can be calculated: $n_i = \psi_i M_a/\rho_a v_i$, where $v_i = \pi D_i^3/6$ is the volume of one aggregate piece, ψ_i is the ratio between the mass of aggregate with characteristic size D_i and the total mass of aggregate, $M_a = (a/c)cV$, and ρ_a is the mass density of aggregate.

The aggregate pieces (particles), assumed to be of spherical shape, are randomly placed in the volume one-by-one through a try-and-reject procedure ensuring that each particle does not overlap with the other particles and is completely contained within the volume of interest [7]. The Delaunay algorithm [18] is then used to connect the centers of the particles through a three-dimensional lattice. Each ridge of the Delaunay tetrahedra identifies a lattice strut connecting two adjacent particles. The cross-sectional area of the lattice struts is defined such that the total volume of the struts corresponds to the considered volume of material (see Ref. [14] for more details).

Along each connecting strut, a point (interaction point), at which the forces between the two adjacent particles (of size D_1 and D_2) are imagined to be transmitted, is defined such that the strut length l is subdivided into two lengths $l_1 = lD_1/(D_1 + D_2)$ and $l_2 = lD_2/(D_1 + D_2)$ (Fig. 1a).

The kinematics of the model is defined assuming that: 1) the axial velocity, $\dot{u}$, is linearly distributed between the particle centers (lattice nodes), and 2) the transverse velocities $\dot{v}, \dot{w}$ are the effect of a rigid motion corresponding to the translational and rotational velocities at particle 1, for side $\overline{13}$, and at particle 2 for side $\overline{24}$ (see Fig. 1a). The transversal velocities at the interaction point can be then computed as $\dot{v}_3 = \dot{v}_1 + l_1\dot{\vartheta}_1$, $\dot{v}_4 = \dot{v}_2 - l_2\dot{\vartheta}_2$, $\dot{w}_3 = \dot{w}_1 - l_1\dot{\varphi}_1$ and $\dot{w}_4 = \dot{w}_2 + l_2\dot{\varphi}_2$, where $\dot{\varphi}$ and $\dot{\vartheta}$ are the rotational nodal velocities orthogonal to the axis of the lattice strut.

The velocity field is then used to define appropriate measures of strain rates at the interaction point: $\dot{\varepsilon}_N = (\dot{u}_2 - \dot{u}_1)/l$, $\dot{\varepsilon}_M = (\dot{v}_4 - \dot{v}_3)/l = (\dot{v}_2 - \dot{v}_1 - l_2\dot{\vartheta}_2 - l_1\dot{\vartheta}_1)/l$ and $\dot{\varepsilon}_l = (\dot{w}_4 - \dot{w}_3)/l = (\dot{w}_2 - \dot{w}_1 + l_2\dot{\varphi}_2 + l_1\varphi_1)/l$, where N is the direction coaxial with the connecting strut and M, L are two mutually orthogonal directions in the plane of the strut cross section.

Finally, the CSL formulation is completed by a constitutive relation characterizing the behavior of the particle interface at the interaction point. Following Ref. [14] normal and shear stresses, are assumed to be proportional to normal and shear strains through damage-like constitutive equations:

$$\sigma_N = \sigma\varepsilon_N/\varepsilon;\ \sigma_M = \sigma\alpha\varepsilon_M/\varepsilon;\ \sigma_L = \sigma\alpha\varepsilon_L/\varepsilon; \tag{1}$$

where $\sigma = \sqrt{(\sigma_N^2 + \sigma_T^2)/\alpha^2}$ = effective stress, $\sigma_T = \sqrt{\sigma_M^2 + \sigma_L^2}$ = shear stress, $\varepsilon = \sqrt{\varepsilon_N^2 + \alpha^2\varepsilon_T^2}$ = effective strain, and $\varepsilon_T = \sqrt{\varepsilon_M^2 + \varepsilon_L^2}$ = shear strain, and α is a material parameter discussed later.

The initial elastic behavior can be formulated through a linear elastic relationship between the effective stress and the effective strain: $\sigma = E_0\varepsilon$. In this case, from Eq. (1) one has $\sigma_N = E_0\varepsilon_N$, $\sigma_M = \alpha E_0\varepsilon_M$, and $\sigma_L = \alpha E_0\varepsilon_L$. As one can see the material parameter α represents the ratio between the shear elastic stiffness and the normal elastic stiffness. In Ref. [15] α was shown to control the macroscopic Poisson's ratio ν: for $\alpha = 0.25$ one obtains $\nu \approx 0.18$.

The elastic modulus E_0 must be computed preserving the different elastic properties of the aggregate pieces and the embedding mortar matrix. Assuming a series coupling, we have

$$E_0 = E_c l/(rl_a + l_c) \tag{2}$$

where E_c is the normal elastic modulus of the embedding mortar, $r = E_c/E_a$ is the ratio between the normal elastic moduli of the embedding mortar and aggregate, $l_a = (D_1 + D_2)/2$ and $l_c = l - l_a$.

The stress–strain evolution remains elastic as long as the effective stress σ does not reach a certain strength limit. Afterwards

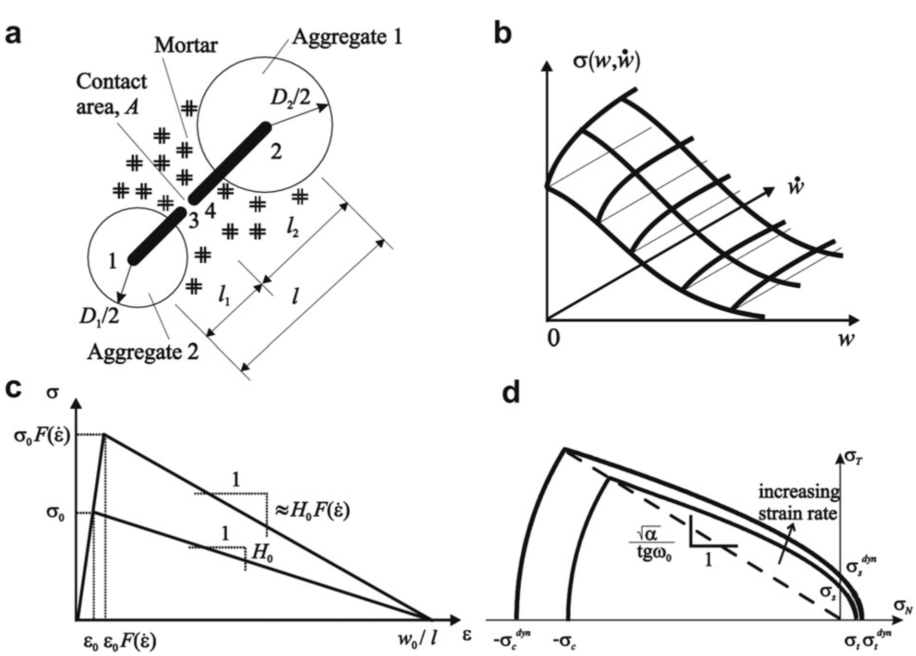

Fig. 1. a) Schematic representation of the lattice strut connecting two adjacent aggregate particles; b) Rate dependent cohesive law; c) Strain-rate dependent linear stress–strain law; d) CSL elastic domain and its rate dependence.