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Numerical modelling of concrete fracture processes under dynamic loading: Meso-mechanical approach based on embedded discontinuity finite elements

Timo Saksala

Laboratory of Civil Engineering, Tampere University of Technology, POB 549, FI-33101 Tampere, Finland

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ABSTRACT

This paper deals with 2D numerical modelling of concrete fracture under dynamic loading. For this end, a mesoscopic modelling approach with an explicit representation of aggregates and different fracture types by rate-dependent embedded discontinuity finite elements is developed. The mortar fracturing is governed by pre-embedded multiple discontinuity finite elements. The aggregates may fail according to the principal stress criterion (mode I) with a single embedded discontinuity. The numerical examples demonstrate that the present model captures many of the experimentally observed features of concrete under low and intermediate strain rates in tension and compression as well as in dynamic Brazilian disc test on concrete. Particularly, the simulations corroborate the hypothesis that the dynamic increase of strength in uniaxial compression and in Brazilian disc test (i.e. the indirect tensile strength) is caused by structural effects due to lateral inertia while in uniaxial direct tension it is a genuine material effect.

1. Introduction

Traditionally, the numerical modelling of concrete structures has been based on phenomenological constitutive models implemented in the finite element method (FEM). These models are based on plasticity theory and/or damage mechanics and treat concrete as a homogeneous material, see [1–6] and relevant chapters in [7]. They can realistically predict the results of structural fracture processes and are still of great importance in structural design, especially in the analyses of massive concrete structures. However, homogenized approach cannot provide any information on the effects of the heterogeneous mesostructure on the complex fracture mechanisms of concrete. In case of concrete, the explicit representation of aggregates is of great importance since the aggregates introduce various fracture toughening mechanisms, such as crack stopping, redirection and branching [8].

For this reason, mesomechanical modelling approach explicitly representing the mesoscopic constituents of concrete has been the topic of many numerical studies (see [8–16]) since the pioneering work by Roelfstra et al. [9]. Describing concrete as a bi-phasic material where the aggregates are embedded in mortar paste matrix has indeed substantially improved the numerical modelling of concrete fracture. The key factor in the above mentioned mesomechanical studies is the fracture (cracking) description. Of these studies, the cracking is described by the discrete or lattice approach in [8,14–16] while [12,13] employ the cohesive interfaces method. Moreover, Gangnant et al. [10] used a damage model, and Pedersen et al. [10] developed a viscoelastic-viscoplastic damage model to describe cracking in the smeared, continuum sense. Finally, the study by Dong et al. [17] using a meshless approach based on the element free Galerkin method is mentioned. However, the focus therein was on modelling a single (or few) crack propagation in a homogenous material.

E-mail address: timo.saksala@tut.fi.

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Nomenclature

A_e	element area
$\mathbf{B}_e$	element kinematic operator
$\mathbf{E}$	elasticity tensor
$\mathbf{f}_t^{\text{ext}}$	external force vector
$\mathbf{f}_t^{\text{int},e}$	internal force vector for element e
G_{Ic}	mode I fracture energy
g	softening slope parameter
$H_{\Gamma_d}^k$	heaviside function at discontinuity k
h_i	softening modulus for discontinuity i
l_d^i	length of discontinuity i
$M_{\Gamma_d}^k$	auxiliary function for discontinuity k
$\mathbf{M}$	lumped mass matrix
N_i	FE interpolation function of node i
$\mathbf{m}_i$, $\mathbf{n}_i$	crack tangent and normal vector
$\mathbf{t}_{\Gamma_d}^i$	traction vector for discontinuity i
Δt	time step
s	viscosity of the material
$\mathbf{u}_i^e$	nodal displacement vector
v_0	constant velocity of BC
$\boldsymbol{\alpha}_d^k$	displacement jump vector
β	shear control parameter
$\boldsymbol{\varepsilon}$	strain tensor
$\dot{\varepsilon}$	strain rate
Γ_d^i	discontinuity i
$\delta_{\Gamma_d}^k$	Dirac's delta function at discontinuity k
κ_i	internal variable of the softening model
$\dot{\lambda}_i$	viscoplastic multiplier
ν	Poisson's ratio
φ_k	ramp function for a discontinuity at node k
ρ	density of the material
$\boldsymbol{\sigma}$	stress tensor
σ_t	tensile strength of the material
$\otimes$	dyadic product operator
∇	gradient operator
$:$	double contraction operator
BC	Boundary Condition
BD	Brazilian Disc
CST	Constant Strain Triangle
DIF	Dynamic Increase Factor
EAS	Enhanced Assumed Strains
FEM	Finite Element Method
ITZ	Interfacial Transition Zone
NCS	Numerical Concrete Specimen

The discrete element or particle methods, while being superior in crack and fragmentation description, require substantially more computational resources than the continuum methods. This is due the fact that contact constraints need to be imposed in compressive loading in the case of the cohesive zone models (see [13]), or algorithms to track the particle configurations and their contacts in the case of particle methods. Therefore, due to the indisputable advantages of the FEM in genuine continuum problems, possibilities to improve its crack description by special enriching techniques have been searched during the last two and half decades. Two most notable approaches of this kind are the element-based enrichment [18,19] (Embedded FEM) and the nodal-based enrichment [20,21] (Extended FEM). The former method is computationally superior due to the local nature of the enrichment which allows for elimination of the extra degrees of freedom (related to the displacement discontinuity) by static condensation. However, it should be mentioned that this advantage is exploited often by relaxing the crack path and crack opening continuity requirements over element boundaries, which prevents the development of a truly discrete crack. If these continuities are enforced, non-constant crack opening modes and special global crack tracking algorithms are often required [22]. Despite these inconveniences, the embedded discontinuity FEM is chosen in the present paper without enforcing the crack path continuity between adjacent elements due to its implementation economy. The embedded discontinuity approach was applied in modelling concrete cracking in [22,23] without, however, accounting for the mesostructure of concrete.

Concrete, as a brittle material, exhibits significant rate-sensitivity both in tension and compression [24–30]. Therefore, as elevated loading rates are often present in engineering structures subjected to dynamic loads, such as explosions and earthquakes, a numerical model with predictive capabilities under dynamic loading is of great importance. Strain-rate sensitivity manifests as an increase in strength upon increasing loading rate accompanied with a transition from single crack-to-multiple fragmentation mode. Moreover, the aggregates, given that they are of considerably higher strength than the mortar, start to fail upon increasing loading rate, which leads to smoother fracture surfaces [24,25,27]. It is thus important that a mesomechanical model for concrete can account for rate sensitivity. Of the above mentioned mesoscopic numerical studies, strain rate effects were considered in [11–13].

In this paper, a mesomechanical approach for concrete fracture under dynamic loading based on embedded discontinuity finite elements is presented. The numerical concrete consists of polygonal or circular aggregates in the cement mortar. The mortar fracturing is represented by pre-embedded multiple discontinuity finite elements while the aggregates, meshed with standard linear triangles, may fail in mode I upon violation of the Rankine criterion. The interfacial transition zone (ITZ) can be accounted for by lowering the strength of the mortar elements in a strip surrounding the aggregates [11]. A multisurface viscoplasticity inspired model for solving the displacement jumps at the discontinuities is employed. Such a model combines some beneficial features of the above discussed numerical methods and alleviates some of their drawbacks. Most notably, it still falls to the category of continuum models and is thus computationally much less demanding than the discrete element models, which are naturally superior in multiple fracture description, or cohesive zone models, which both require the imposition of contact constraints.

The performance of the present model is extensively tested in 2D simulations of uniaxial tension and compression tests under various strain rates. Moreover, the effect of the main model parameters as well as the size, distribution, and shape of aggregates and the numerical samples are tested. The effect of the ITZ is tested as well. Specifically, the hypothesis that the lateral inertia is responsible for the increase in DIF in uniaxial compression is investigated. Finally, the dynamic Brazilian disc test on concrete is simulated as a further validation of the model.