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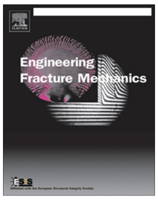

Phase-field simulation of interactive mixed-mode fracture tests on cement mortar with full-field displacement boundary conditions

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ABSTRACT

Phase-field modeling is an elegant approach to simulate complicated fracture processes, including crack initiation, propagation, merging and branching in a unified framework without the need for ad-hoc criteria and on a fixed mesh. These capabilities can only be fully validated through the comparison with experiments featuring crack development histories and patterns of sufficient complexity. As opposed to conventional mixed-mode fracture tests with predefined loading, interactive tests with multiaxial loading which are controlled during the propagation of the cracks can create more complex and stable crack propagation patterns. Moreover, the development of measurement techniques such as digital image correlation (DIC) provides the possibility to quantitatively characterize the full-field kinematics during the tests. In this work, full-field displacements measured by DIC during interactive mixed-mode fracture tests on cement mortar specimens are adopted as boundary conditions for phase-field numerical simulations. Qualitative and quantitative comparisons are illustrated, demonstrating the capability of the phase-field approach to predict complex mixed-mode fracture phenomena in cement mortar and suggesting possible further developments.

1. Introduction

The prediction of fracture phenomena in concrete, which is of interest for several technical applications, still represents a challenge for the computational modeler. Within multiscale approaches, concrete can be regarded as consisting of cement mortar, including the cement matrix and the smallest aggregates, and the largest aggregates. In the majority of cases, cracking occurs in the cement mortar and is a complex process featuring local mixed-mode conditions.

Among the best known experimental setups for the investigation of mixed-mode fracture of concrete are the three-point bending tests with asymmetric notch location [1–3], the tests on hollow cylindrical specimens adopted by Keuser and Walraven [4], the tests on double-notched specimens by Nooru-Muhamed [5], the torsion fracture test developed by

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Nomenclature

E	Young's modulus
$\mathcal{E}$	energy functional
$\mathcal{E}_l$	energy functional with regularization treatment
F_Y	shear force
F_Z	normal force
G	Lamé constant
G_c	fracture energy
$\mathcal{H}^+$	history variable ensuring an irreversibility condition on s
$\boldsymbol{I}$	second-order identity order
K	bulk modulus
ℓ	length parameter
$\boldsymbol{n}$	outward normal unit vector to the boundary
$\boldsymbol{O}$	point for rotation
R_X	rotation along X
R_Y	rotation along Y
R_Z	rotation along Z
s	phase-field parameter
t	time
$\bar{\boldsymbol{t}}$	prescribed traction on the Neumann portion of the boundary $\partial\Omega_{\bar{\boldsymbol{t}}}$
$\boldsymbol{u}$	displacement
$\bar{\boldsymbol{u}}$	prescribed displacement on the Dirichlet portion of the boundary $\partial\Omega_{\bar{\boldsymbol{u}}}$
$\boldsymbol{x}$	spatial coordinate

Greek symbols

Γ	crack surface
$\boldsymbol{\varepsilon}$	strain
$\mathrm{tr}(\boldsymbol{\varepsilon})$	volumetric strain
$\boldsymbol{\varepsilon}_{\mathrm{dev}}$	deviatoric strain
$\boldsymbol{\varepsilon}_c$	critical strain
η	small dimensionless parameter
λ	Lamé constant
ν	Poisson ratio
$\boldsymbol{\sigma}$	stress
$\boldsymbol{\sigma}_c$	critical stress
$\psi_{\mathrm{el},0}$	elastic strain energy density
ψ_{el}	elastic strain energy density with regularization treatment
ψ_{el}^+	positive part of elastic strain energy density with regularization treatment
ψ_{el}^-	negative part of elastic strain energy density with regularization treatment
Ω	open bounded domain
$\partial\Omega_{\bar{\boldsymbol{t}}}$	Neumann boundary of the domain
$\partial\Omega_{\bar{\boldsymbol{u}}}$	Dirichlet boundary of the domain

Acronyms

DIC	digital image correlation
RT3	regularized three-noded triangles

Brokenshire [6], and the tests on L-shape specimens proposed by Winkler [7]. Each of these tests has advantages and disadvantages, see [8].

New experimental techniques have recently brought the possibility of quantitatively investigating mixed-mode fracture in cementitious materials (more general in brittle and quasi-brittle materials) to a new level. In this paper, we will be focusing on the tests in [8]. Two crucial developments were exploited in this experimental campaign: (i) the use of a multiaxial electromechanical testing machine, i.e. of a hexapod [9,10] (6 degrees of freedom) with an optical 3D displacement control loop [11]. This testing machine can apply a complete twist (3 translations + 3 rotations), wrench (3 moments + 3 forces) or a combination of both to the boundary of the specimen; (ii) the digital image correlation (DIC) technique [12], through which the full displacement field on each face of the sample becomes available. This gives access to the actual boundary conditions, which are essential for a more realistic computational modeling, and provides an enhanced capability of quantitative

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