Engineering Fracture Mechanics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Two-dimensional simulations of concrete fracture at aggregate level with cohesive elements based on X-ray μCT images

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A R T I C L E I N F O

Article history:
Received 30 April 2016
Received in revised form 13 September 2016
Accepted 29 September 2016
Available online xxxx

Keywords:
Concrete beam
Cohesive elements
Interfacial transitional zones
Fracture
Meso-scale finite element method
X-ray μCT

A B S T R A C T

The paper presents results of two-dimensional meso-scale simulations of fracture in notched concrete beams subjected to three-point bending test. Concrete was assumed as a 4-phase material composed of aggregate grains placed in the cement matrix, interfacial transitional zones (ITZs) and macro-voids. The particle distribution was taken from real concrete beams on the basis of X-ray μCT images. Comprehensive numerical analyses were carried out using the 2D meso-scale finite element method (FEM) with cohesive elements located in the cement matrix and along the ITZs. In addition, parametric studies were carried out for different material constants. The effect of the shape, content and density of aggregate packing was also investigated. A satisfactory agreement with respect to the load-displacement and crack geometry was achieved between FE analyses and experiments.

1. Introduction

Concrete is a highly heterogeneous quasi-brittle material wherein fracture process is a fundamental phenomenon [1–3]. The onset of micro-cracks in a hardening part of the stress-strain curve is followed by a formation of dominant macro-cracks in a softening regime. Concrete fracture is very complex due to the occurrence of phenomena such as: branching, coalescence, kinking, tortuousness and interlocking of cracks. The understanding of a fracture process is of major importance to ensure the safety of structures. The experiments and numerical simulations evidently show that the concrete fracture behaviour depends on meso-structure (e.g. aggregate volume, aggregate size, aggregate roughness, aggregate stiffness, particle size distribution curve, mortar volume and macro-porosity). In order to realistically describe the concrete fracture behaviour, its internal structure should be taken into account at least at the meso-scale. In particular, the aggregate presence is crucial as its volume fraction in concrete may be approximately 70–75% [4]. Since fracture process begins in interfacial transitional zones (ITZs), thus it is crucial to properly determine their properties. ITZs are a porous region of the cement paste around aggregate particles which is perturbed by their presence [5–7]. Their width is about 0–50 μm depending upon the aggregate roughness. The concrete meso-scale behaviour may be modelled with continuous [8–14] and discontinuous models [15–17] within continuum mechanics. It may be also described using discrete models which include lattice models [18–21], discrete element method (DEM) [22–25], interface element models with constitutive laws based on non-linear fracture mechanics [26,27] and rigid body-spring models [28–30]. Continuous constitutive models suffer from the finite element mesh sensitivity and numerical results do not coincide as a mesh is refined. Therefore, the classical models need to be enhanced with the

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http://dx.doi.org/10.1016/j.engfracmech.2016.09.012
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Nomenclature

B	beam width
$\boldsymbol{C}$	bulk stiffness matrix
d_{50}	mean particle diameter
d_a	aggregate grain diameter
d_m	macro-void diameter
$d_{\max}$	maximum aggregate diameter
D	scalar damage variable
E	modulus of elasticity
f_c	uniaxial compressive strength
f_t	uniaxial tensile strength
$f_{t,flex}$	tensile strength under bending
F	vertical force (load)
G_F	tensile fracture energy
h_c	crack height
H	beam height
k_n, k_s	actual normal and tangential diagonal components of stiffness matrix $\boldsymbol{K}$
k_{n0}, k_{s0}	initial normal and tangential diagonal components of stiffness matrix $\boldsymbol{K}$
$\boldsymbol{K}$	stiffness matrix of cohesive elements
l_c	crack length
L	beam length
s	finite element size
$\boldsymbol{t}$	traction vector
t_n, t_s	normal and tangential components of traction vector
t_{n0}, t_{s0}	critical normal and tangential components of traction vector (strength)
u	beam deflection
α	softening curve parameter
$\boldsymbol{\delta}$	relative displacements vector
δ_m	effective relative displacement
δ_m^0	effective relative displacement at damage initiation
δ_m^f	effective relative displacement at decohesion
δ_m^{max}	maximum effective relative displacement
δ_n, δ_s	normal and tangential components of relative displacement vector
$\boldsymbol{\varepsilon}$	strain vector
ν	Poisson's ratio
$\boldsymbol{\sigma}$	stress vector
2D	two-dimensional
3D	three-dimensional
CMOD	crack mouth opening displacement
COH2D4	4-node two-dimensional cohesive finite element
CPS3	3-node linear plane stress finite element
DEM	discrete element method
FE	finite element
FEM	finite element method
ITZ	interfacial transitional zone
µCT	micro computed-tomography
'a'	aggregate
'cm'	cement matrix

characteristic length of micro-structure in order to tackle the aforementioned numerical problems. This extension can be performed with different theories: micro-polar [31–33], strain gradient [34–38] viscous [31,34] and non-local one [39–44]. In contrast, numerical models using cohesive elements or the eXtended Finite Element Method for modelling fracture do not need to be regularized with the aid of a characteristic length, since a crack or shear zone is created in a discrete way. For this reason the discontinuous approaches are very popular and widely used in fracture studies [3,45,46].

The main aim of this paper was to investigate a complex fracture process in a concrete beam subjected to three-point bending test by means of the 2D meso-scale FEM with zero in-plane thickness interface elements embedded in the initial mesh of solid (bulk) elements. In order to simulate fracture in concrete, the interface elements were equipped with a crack initiation criterion and a traction-separation law [15–17]. The material heterogeneity was taken into account by considering 4 different phases (aggregate, cement matrix, ITZs, macro-voids) and assigning different material properties to each phase.

Please cite this article in press as: Trawiński W et al. Two-dimensional simulations of concrete fracture at aggregate level with cohesive elements based on X-ray µCT images. Engng Fract Mech (2016), http://dx.doi.org/10.1016/j.engfracmech.2016.09.012