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Dynamic fracture behaviour in fibre-reinforced cementitious composites

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ABSTRACT

The object of this work is to simulate the dynamic fracture propagation in fibre-reinforced cementitious composites, in particular, in steel fibre reinforced concrete (SFRC). Beams loaded in a three-point bend configuration through a drop-weight impact device are considered. A single cohesive crack is assumed to propagate at the middle section; the opening of this crack is governed by a rate-dependent cohesive law; the fibres around the fracture plane are explicitly represented through truss elements. The fibre pull-out behaviour is depicted by an equivalent constitutive law, which is obtained from an analytical load–slip curve. The obtained load–displacement curves and crack propagation velocities are compared with their experimental counterparts. The good agreement with experimental data testifies to the feasibility of the proposed methodology and paves the way to its application in a multi-scale framework.

1. Introduction

The industrial use of fibre reinforced cementitious composites, in particular steel fibre reinforced concrete (SFRC), in structural applications has increased significantly during the last decades. However, in order to optimise the design with fibre reinforced material and spread its applications, a complete understanding and modelling of the material behaviour under both static and dynamic loading conditions are necessary.

Depending on whether the fibres are explicitly represented or not, numerical models on fibre-reinforced concrete (FRC) can be roughly classified as explicit or homogeneous ones. Examples of the former and the later can be found in Padmarajaiah and Ramaswamy (2002), Voo and Foster (2004), Cunha et al. (2012), Laranjeira (2011), Kang et al. (2014), Thomée et al. (2005) and Strack (2008) respectively. However, most of them are dealing with static loading conditions. In spite of abundant experimental results available for FRC materials under impact loading (Al-Oraimi and Seibi, 1995; Banthia et al., 1996, 1998a, 1998b, 1999a, 1999b; Bindiganavile and Banthia, 2001; Sukontasukkul et al., 2001; Bindiganavile et al., 2002; Bindiganavile and Banthia, 2005; Chan and Bindiganavile, 2010; Tassew et al., 2012; Abu-Lebdeh et al., 2012; Zhang et al., 2014, 2015), publications on numerical modelling for dynamic fracture propagation are rather scant.

The explicit modelling of the fibres has its origin in the explicit description of rebars in concrete elements. The first of such attempts dates back to the work by Ngo and Scordelis (1967). Reinforcing bars were represented as series of truss

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Nomenclature

B	width of a three-point bend (TPB) beam
D	height or depth
E	Young's modulus of concrete matrix
E_s	elastic modulus of steel fibres
F	pull-out load
G_F	specific fracture energy
L	beam length
L_f	fibre length
L_e	effective fibre embedment length
L_{h_c}	critical fibre embedment length
P	applied external load
P_{max}	peak load
S	beam span
c	longitudinal wave speed
c_1, c_2	hardening coefficient and viscosity parameter for Peirce's model
d_f	fibre diameter
f_c, f_t	compressive and tensile strength
f_u	ultimate strength
l_{ch}	material characteristic length
s	slip length
t_{ch}	intrinsic time scale
v	crack-propagation velocity
w	crack-opening displacement
w_c	critical crack-opening displacement
$\dot{w}$	crack-opening velocity
$\dot{w}_0$	cutoff crack-opening velocity
η_θ	orientation number
α_f, α_w	coefficients for the rate-dependent cohesive law
δ	loading-line displacement
$\dot{\delta}$	loading-line displacement rate
ε_u	ultimate strain
κ	fibre–matrix interface bond modulus
μ	friction coefficient at the fibre–matrix interface
ρ, ρ_s	matrix and steel fibre density
σ_0	static yield strength
τ_{max}, τ_f	maximum shear and frictional bond strength
θ_m	average fibre inclination angle

elements, connected to the concrete through link elements representing the nonlinear bond properties of the concrete–bar interface. The modelling of bond breakdown and slip is essential for estimating crack openings and other mechanical aspects that affect the safety and serviceability of concrete structures (Ruiz, 2001). Simulating both the concrete bulk and the reinforcing bars as volumetric elements, consequently, explicitly representing the interface in-between (Yu and Ruiz, 2006; Yu et al., 2011) is another alternative. The gradual deterioration of the bond and the interaction between the concrete bulk and reinforcements were clearly represented through such an explicit methodology. The computation time involved, however, prevents its extension to fibre reinforced material modelling.

In terms of computational efficiency, discrete lattice-based models have been successfully used in the literature for simulating fracture behaviour of FRC under static loads. For instance, in the work of Bolander and Saito (1997) and Kunieda et al. (2011), the matrix cells are linked through additional spring elements that represent the fibres crossing through their boundaries. Recently, Kang et al. (2014) described a computationally efficient approach to represent individual fibres and their composite behaviour, within lattice models of cement-based materials. By assuming a perfectly-plastic stress–strain relation for the fibre and a slip-hardening behaviour for the matrix–fibre interface, they first obtained pull-out forces for a single fibre, then distributed these forces along the embedded lengths of the fibres that bridge a developing crack. The fibres do not possess their own degrees of freedom, instead, they are embedded within a rigid-body-spring representation of the matrix phase. In an equivalent way, the fibres can be freely positioned within the computational domain irrespective of the discretisation of the matrix phase.

Another explicit approach is the finite element method developed by Cunha et al. (2012), who modelled the SFRC as two different phases: one homogeneous and continuous phase for the concrete, and the other discrete and discontinuous phase for the fibres. The fracture process in the cement matrix is simulated by means of a multi-fixed smeared crack model.

All the above-mentioned numerical models dealt with static loading conditions. Despite the fact that there are several models oriented to reproduce composite material behaviour under dynamic and impact loading, the model of Teng et al. (2008) is the first one we have found in the literature which was entirely designed to dynamic FRC simulations. Teng's model uses LS-DYNA software in order to simulate a projectile impact over a SFRC slab. The material is modelled by means of a hydrodynamic model for elastoplasticity, which allows a good simulation of the non-linear softening behaviour after the fracture and can be defined using the experimental information from a uniaxial compressive test. Mie–Gruneisen's state equation is employed in this model. The dynamic increase factor (DIF) was considered the same in steel fibre reinforced concrete as in regular plain concrete.

The example to treat dynamic fracture in FRC with explicit fibres is the axisymmetric model introduced by Xu et al. (2012). They studied the SFRC behaviour under different strain rates involved in a split-Hopkinson pressure bar test. The employed model is a mesoscale one, in which fibres, aggregates and the cementitious matrix are explicitly simulated. This kind of meso-scale framework has obtained good results in plain concrete simulation (Zhou and Hao, 2008), therefore seemed promising to be extended for FRC materials. The cementitious matrix is depicted as a plastic material, a DIF for compression and tensile strength based on experimental results is used. Aggregates are simulated as circular shapes of various sizes, randomly distributed in the bulk using the same constitutive equations as that of the bulk matrix. Fibres were simulated in its complete shape, including the hooked-ends with actual fibre steel properties and randomly distributed.