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Discrete fracture in high performance fibre reinforced concrete materials

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A B S T R A C T

In this paper a simple, but effective methodology to simulate opening mode fracture in high performance fibre reinforced concrete is presented. The main contribution of the paper is a technique to extrapolate the load displacement curves of three point bending experiments on fibre reinforced concrete. The extrapolation allows the full work of fracture to be determined, from which the fracture energy may be obtained. The fracture energy is used in the definition of a cohesive softening function with crack tip singularity. The softening relation is implemented in an embedded discontinuity method, which is employed for the numerical simulation of three point bending experiments. The experimental work includes a size effect study on three point bending specimens. The numerical simulation provides a satisfactory prediction of the flexural behaviour and the size effect observed in the experiments.

1. Introduction

Unlike other fields of engineering, the adoption of fracture mechanics in civil engineering practice has been slow. A strong case for the use of fracture mechanics can be made however, in particular for the design of concrete structures, since concrete exhibits considerable size effect in fracture [1]. A reason for the slow adoption may be the perceived complexity associated with design using fracture mechanics approaches and the specialized testing involved.

The materials under study in this paper are high performance concrete mixes developed for use in an innovative pavement system known as Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP). A key parameter in the design of UTCRCP, and concrete pavements in general, is the nominal tensile strength (σ_{Nu}) of the material. σ_{Nu} is determined from the peak load recorded in bending tests on beams, assuming a linear elastic stress distribution. Earlier work has shown σ_{Nu} for the high performance fibre reinforced UTCRCP material to be subject to significant size effect [2]. As a consequence, generalizing the σ_{Nu} value obtained from beam bending tests to the design of three dimensional pavement structures is problematic. To overcome the size effect problem, a need exists to develop reliable, but simple, fracture mechanics based method to predict the structural performance of UTCRCP material in bending.

The objective of the paper is to numerically simulate mode I (opening mode) fracture in high performance fibre reinforced concrete. To characterize the fracture behaviour and enable numerical simulation, the fracture energy of the material needs to be determined. A methodology is developed to accurately measure the full work of fracture (W_f) required to break fibre reinforced concrete specimens in Three Point Bending (TPB) tests. From W_f, the specific fracture energy (G_f) of the material is

Abbreviations: CMOD, Crack Mouth Opening Displacement; EDM, embedded discontinuity method; FRC, fibre reinforced concrete; TPB, Three Point Bending; UTCRCP, Ultra-Thin Continuously Reinforced Concrete Pavement.

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Nomenclature

a	notch depth (mm)
A	empirical constant (N)
b	width of specimen (mm)
E	modulus of elasticity (GPa)
f_c	compressive strength (MPa)
f_t	tensile strength (MPa)
G_f	fracture energy (N/mm)
h	height of specimen (mm)
L	specimen length (mm)
P	load (N)
P_u	peak load (N)
s	span (mm)
W_f	work of fracture (N mm)
W_{tail}	work of fracture under modelled P–δ tail (N mm)
w	crack width (mm)
w_c	critical crack width (mm)
y	position along vertical axis of beam (mm)
δ	deflection at midspan (mm)
ν	Poisson's ratio
σ	crack bridging stress (MPa)
σ_{Nu}	nominal tensile strength (MPa)
φ	angle of rotation (rad)

determined. G_f is used in the definition of a cohesive softening function with crack tip singularity. The cohesive crack relation for the material thus obtained allows simulation of the fracture behaviour observed in TPB tests. The experimental programme for this study includes TPB specimens of different sizes produced from two UTCRCP mix designs. Numerical simulation is performed with an Embedded Discontinuity Method (EDM) implemented in an open source finite element framework.

2. Determining the fracture energy of fibre reinforced concrete from TPB tests

The work of fracture (W_f) required to completely break a specimen in a TPB test is represented by the area under the load–deflection (P–δ) curve, or load–Crack Mouth Opening Displacement (CMOD) curve. The deflection (δ) is the vertical displacement of the specimen at midspan measured in the experiments. The CMOD is gauged over the mouth of the notch in TPB tests on pre-notched samples. In the experiments performed as part of this study both the δ and the CMOD were recorded. Fig. 1a shows the load–deflection curves obtained for a group of specimens tested. A schematic representation of the TPB test configuration is shown in Fig. 1b.

The energy required to produce a unit of fractured area G_f, is calculated for the concrete–fibres composite material using:

$$G_f = \frac{W_f}{b(h-a)} \tag{1}$$

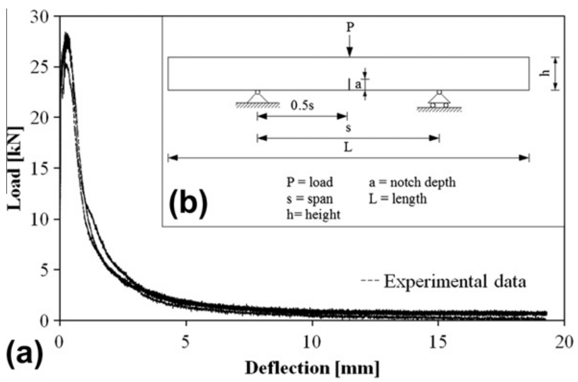

Fig. 1. (a) Load–deflection curve for TPB test and (b) TPB test configuration.