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A two-phase material approach to model steel fibre reinforced self-compacting concrete in panels

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ABSTRACT

This work presents an experimental and numerical approach to ascertain the mechanical behaviour of steel fibre reinforced self-compacting concrete in laminar structures. Four-point flexural tests were performed on prismatic specimens extracted from a SFRSCC panel; the specimens' behaviour was then modelled under the FEM framework. SFRSCC is assumed as a two-phase material, i.e. plain concrete and discrete steel fibres. The non-linear material behaviour of the plain matrix was simulated using 3D smeared crack model, while the fibre reinforcement mechanisms were modelled using micro-mechanical behaviour laws determined from experimental fibre pull-out tests. The good performance of the developed numerical strategy was demonstrated.

1. Introduction

In the past decades, the development of steel fibre reinforced self-compacting concrete (SFRSCC) technology for structural applications has been pushed forward by increasingly higher concrete construction industry requirements. The adoption of this material can partially, or even fully, exclude the use of conventional steel reinforcement, since steel fibres are able to provide significantly higher post-cracking tensile strength than an equivalent strength class unreinforced self-compacting concrete (SCC). Several researchers have shown that the incorporation of discrete fibres can improve both toughness and durability of concrete due to the crack width restraint [1–3]. However, the tensile performance of SFRSCC, and in particular the post-cracking strength, depends, among other factors, on how fibres are distributed and oriented in the matrix, since this also contributes to the grade of fibre reinforcement efficiency. In laminar structures, a proper knowledge and better understanding of the fibre distribution/orientation parameters can enable a better estimation of the material post-cracking strength and, consequently, to reduce the material properties scatter [4]. In order to accurately predict the tensile behaviour of SFRSCC, it is crucial to understand how fibres are distributed, as well as oriented within the composite bulk. In the case of SFRSCC, fibre distribution/orientation is influenced, mainly, by the properties in the fresh state of concrete (flowability) and wall effects [4–6]. This leads to the variation of the post-cracking parameters through the specimen. Therefore, assuming SFRSCC as an isotropic material could lead to an unrealistic estimation of the mechanical performance of a certain structural element.

In general, the stress – crack opening displacement relationship, $\sigma - w$, can be used to estimate the post-cracking response of low content fibre reinforced concrete [7]. Several analytical micro-mechanical models are available in literature

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Nomenclature

a	depth of the notch
A_f	fibre's cross section area
b_{rct}	width of the specimens
C_f	fibre content
d_f	fibre's diameter
$\underline{D}$	tangential constitutive matrix
f_{ct}	material tensile strength
f_{R1}	residual flexural strength for a CTOD = 0.5 mm
f_{R3}	residual flexural strength for a CTOD = 2.5 mm
F	force
G_f^I	mode I fracture energy
h	total depth of the specimen
h_{rct}	height of the prismatic specimen
$\underline{K}^{crco}$	solid finite element stiffness matrix
$\underline{K}^{rc}$	stiffness matrix of a SFRSCC solid finite element
$\underline{K}_i^f$	stiffness matrix of the i^{th} fibre
l_b	crack band width
l_f	fibre's length
l_{rct}	length of the specimens
m_f	mass weight of a single fibre
n	vector normal to the crack plane
n_f	total number of the embedded fibres in the mother-element
N^f	number of fibres per unit area
N_T^f	total number of fibres
$N_f^{vol.}$	total number of fibres contained in the specimen
s	fibre's slip
$\hat{u}_i$	fibre orientation versor
V_{sp}	volume of specimen
x_i, y_i, z_i	fibre's centre of gravity coordinates
y	distance between LVDT and the notch mouth of the specimen
α	fibre's inclination angle
β	angle between the expected concrete flow and notch direction
$\Delta\underline{\varepsilon}$	strain vector increment
$\Delta\underline{\varepsilon}^{co}$	incremental strain vector of the concrete in between cracks
$\Delta\underline{\varepsilon}^{cr}$	incremental crack strain vector
$\Delta\underline{\sigma}$	stress vector increment
ε	strain
ε_f	fibre's strain
$\varepsilon_{n,ult}^{cr}$	ultimate crack normal strain
η_θ	fibre orientation factor
θ	angle between the fibre's longitudinal axis and a versor orthogonal to the cut plane
$\xi_{x,y,z}$	coordinates of a uniform random number
σ	stress
σ_f	fibre's stress
$\sigma_{n,1}^{cr}$	material tensile strength
$\hat{\upsilon}$	plane's normal versor
CMOD	crack mouth opening displacement
CTOD	crack tip opening displacement
SCC	self-compacting concrete
SFRSCC	steel fibre reinforced self-compacting concrete

to predict the tensile performance of steel fibre reinforced concrete, SFRC, assuming a random fibre distribution [8–11]. These models are principally based on averaging the contribution of the individual fibres transferring stresses across a crack plane. However, in the case of SFRSCC structures, an anisometric fibre structure was expected, mainly, due to the high flowability of the self-compacting concrete [4]. In addition, the post-cracking behaviour of the composite is also strongly influenced by the micro-mechanical properties of a single fibre. In fact, the knowledge of the fibre bond stress – slip behaviour, conjugated with an accurate fibre distribution, can render a good estimation of the composite mechanical properties [12]. SFRSCC can be assumed and modelled as a two-phase material, namely, the plain concrete phase (aggregate and