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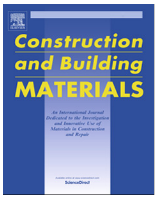

A bibliography on the analytical model of the mechanical behaviour in uniaxial tension of fibre concrete: Application to concrete reinforced with fibres and powders from recycling of thermoset composite materials

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HIGHLIGHTS

- Local bending of fibres at an angle β increases the stability of fibres to pullout.
- The tensile strength of FRCs is obtained with a fibre orientation from 42° to 55°.
- The best post-peak response would be obtained with an orientation of 42–55°.

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ABSTRACT

This article presents a qualitative and quantitative observation of composite rupture under uniaxial tension and analytical modelling of behaviour under uniaxial tension. The chapter begins with a bibliographic review of the numerical and analytical models in the literature. Then follows an analysis of rupture processes during tension testing in order to define an analytical model for softening (or post peak) behaviour of Fibre and Powder Reinforced Concrete (FPRC).

Modelling is at meso-level, taking into account fibre-matrix interactions and their number and orientation through crack(s) as basic parameters. The modelling is applied to 11.54% fibre and powder reinforced concretes. Powders are considered as short fibres 400 μm long.

1. Introduction

This section presents a detailed analysis of the rupture process under tension. Rupture under tension of all types of fibre-reinforced concrete can be subdivided into 4 major phases (Fig. 1) [1–4]:

- ***Elastic domain "O":*** Response to tension in the elastic phase is almost linear. Tensile stress is proportional to the deformation (see Fig. 2).

- ***Microcracking "A":***

According to Van Mier, microcracking is probably the most significant phenomenon in the tensile response of concrete [3]. The tensile strength of the material is strongly dependent on its response during the microcracking phase. In addition, at structural level, durability and permeability depend on both the size and number of microcracks present. A crack can be defined as a displacement discontinuity in the structure. In cementitious materials cracks may be of different sizes (for example, micro- and macrocracks). The classification of cracks by size, however, is not clear (see Fig. 2).

In this work, the term "microcracks" will be used for cracks of a length approximately equal to the average diameter of the aggregates in the composition of the material (here the average diameter is around 0.5 mm). The width of a microcrack in normal weight unreinforced concrete depends on its length, whereas for reinforced concretes it depends on crack initiation resistance. According to Mobasher, the width of microcracks observed in experiments with fibre reinforced concretes is around 8.0 μm [5] and between 1.5 and 13.6 μm according to Otsuka [6].

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Nomenclature

FPRC	fibre and powder reinforced concrete
HPFRC	high performance fibre reinforced concrete
FRC	fibre reinforced concrete
SFRC	steel fibre reinforced concrete
$A_{f,1}$	surface area of the cross section of a single fibre [mm^2]
D	diameter [mm]
$E_{1\text{-}2}$	energy needed to create the first crack in the multiple cracking sequence of HFC [N mm]
E_2	energy needed to create the second and al other cracks in the multiple cracking sequence in HFC [N mm]
E_f	the modulus of elasticity of the fibres (Ef 210000 N/mm^2) [N/mm^2]
G_{II}	the fracture energy released at the fibre-matrix interface during the debonding process (the fracture energy of the second (II) mode – i.e. of the shear fracture) [N mm]
G_m	the fracture energy of plain concrete, obtained from the tensile test [N mm]
G_mV_m	the fracture energy of the matrix, required to create a new through-crack surface (where *Gm* is the matrix fracture energy, and *Vm* the matrix volume fraction in %) [N mm]
N	total number of fibres present in the cross-section of a FRC element [-]
N	normal force [N]
F_{arr}	pullout force in fibre [N]
$P(w)$	*PII* = the horizontal component of the total bridging force, equal to the total tensile force that acts on the fibre-concrete composite element [N]
$\mathrm{F_b}(w)$	total tensile force in the fibre inclined under the angle b (w) [N]
S	spacing of fibres in a cross-section of a FRC specimen [mm]
U_{db}	the debonding energy, needed to destroy the elastic bond at the fibre-matrix contact [N mm]
V_{cont}	the volume of the container [m^3]
V_d	ratio of disturbed volume of container and total volume of container [-]
V_{ef}	the effective volume quantity of fibres [-]
V_f	fibre volume percentage [N/mm^2]
V_f	the applied volume quantity of fibres [-]
V_m	1- *Vf* the matrix volume fraction [-]
V_{nd}	ratio of non-disturbed volume of container and total volume of container [-]
aij	loosening (opening) coefficient for interactions between grains [-]
b	width of the cross-section of a structural element [mm]
d	fibre diameter
E_b	modulus of elasticity of concrete [N/mm^2]
f_t	uniaxial tensile strength of concrete [N/mm^2]
$f_{t,0}$	tensile strength of plain concrete [N/mm^2]
$f_{t,cr}$	first-cracking strength of FRC loaded in uniaxial tension [N/mm^2]
f_y	tensile strength f steel fibres [mm]
L_f	fibre length [mm]
l/d	fibre aspect ratio [-]
L_{db}	debonded length of a single fibre during its pullout [mm]
l_{max}	selected maximum visible fibre length for different fibre length distributions [mm]
$n_{act}\ (w)$	the number of fibres active at the crack bridging for the crack width w [-]
n_{tot}	total number of fibres present in the cracked cross section [-]
$p(w)$	the probability that the fibres active in crack bridging may be found at the crack width w [-]
ω	crack width [mm]
Δ	fibre slip during pullout [mm]
$\mathrm{D}_{Uf\ -\ mc}$	the increase of fibre strain energy by virtue of the action of the fibres in bridging the first through-crack [N mm]
$\Delta_{Uf\ -\ mu}$	the increase in the fibre strain energy, as a result of the bridging of cracks during multiple cracking [N mm]
Δ_{Ufr}	the frictional energy, absorbed by virtue of the difference in strain (slip) of the fibres bridging the first through-crack and the concrete matrix which surrounds them [N mm]
Δ_{Ufm}	the decrease of the matrix strain energy (since the strain in a cracked matrix is zero) [N mm]
α	the angle of inclination i.e. orientation of a fibre [-]
$\beta(w)$	the angle of local bending of an inclined fibre at the crack width w [°]
$\beta\ (w)$	the angle of local bending of fibre across the crack [°]
β_{max}	maximum local bending angle of the fibre across the crack [°]
β_{min}	minimum local bending angle of the fibre across the crack [°]
ε	strain in general
$\varepsilon_{\beta,\omega2}$	tensile strain of HPFRC at the crack width *w*2 for the design stress-strain relation [-]
$\varepsilon_{b,\omega1}$	tensile strain of HPFRC at the crack width *w*1 for the design stress-strain relation [-]
ε_{mu}	the strain at which the first through-crack forms in the fibre concrete under consideration [-]
η	the coefficient of orientation of fibres, ($0 < h < 1$, $h = 1$ for fibres fully oriented in the direction of the main tensile stress)
η	factor for triangular and square fibre array
σ	stress in general (tensile or compressive) [mm]
τ	shear stress along the fibre matrix interface [N/mm^2]
τ_f	the average frictional stress at the fibre-matrix interface, which exists after the debonding at the interface has been finished [N/mm^2]

- ***Macrocracking "B"***

This phase characterises cracks from the microcracking stage with numerous very fine cracks spread throughout the sample until crack bridging, which generally occurs with the presence of a dominant crack. If the tensile load on the concrete continues after microcracks form, the microcracks propagate and join up with each other to create a macrocrack. As a first approximation, it can be assumed that a macrocrack has a length equal to twice the largest particle size (see Fig. 2).

This section defines a macrocrack, based on the uniaxial tensile tests conducted, as a crack that propagates throughout the entire transversal section of the cylinder. Tensile stress associated with the formation of the initial crack is known as "first-cracking stress". The first crack to form in the samples indicates the start of the macrocracking phase. The first crack corresponds to the first deviation following the linear elastic domain of the stress-strain diagram (σ-ε) (Fig. 3).

During macrocrack initiation and propagation, the tensile load must be transferred through the cementitious matrix to other elements in the composite that can take up the load. In the case of unreinforced normal weight concrete, hardly any stress transfer is possible because the cementitious paste is weak after the peak. Thus the post peak phase B where "macrocracks" occur is extremely short [4].