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A semi-analytical model to predict the pull-out behaviour of inclined hooked-end steel fibres

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HIGHLIGHTS

- ▶ The pull-out of different types of fibres embedded in a mortar matrix is investigated.
- ▶ The fibre geometry, strength, embedded length and inclination angle affect the pull-out behaviour.
- ▶ Increasing the pull-out inclination angle increases the chance of fibre rupture.
- ▶ A combination of low strength fibre with high strength matrix enables fibre rupture.
- ▶ All observed pull-out curves can be simulated by the proposed semi-analytical model.

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ABSTRACT

The residual post-cracking tensile strength of conventional steel fibre reinforced concrete is directly related to both the amount of fibres crossing a crack and the individual pull-out responses of all activated fibres. Therefore, the knowledge of the single pull-out behaviour is essential to understand the uni-axial or bending behaviour of SFRC when it is considered as a full-fledged composite. Since hooked-end steel fibres are considered to be the most suitable fibre type for structural purposes, the need to accurately predict the pull-out response of these type of fibres, is of great practical importance. In this paper, an experimental investigation of the pull-out response of both straight and hooked-end steel fibres is discussed. Based on the obtained experimental data, a semi-analytical model is developed to predict the fibre pull-out behaviour. The ability of the model to deal with different geometrical and mechanical fibre characteristics as well as the influence of orientation, embedded length and matrix compressive strengths, reflects its overall quality.

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1. Introduction

Hooked-end steel fibres are added to concrete to improve its toughness in the hardened state when it is subjected to bending or uni-axial tension. When cracking occurs, fibres are activated and they start to transfer tensile forces between both crack surfaces. This crack-bridging ability results into the post-cracking strength of steel fibre reinforced concrete (SFRC).

In the past few decades, several researchers modelled the residual strength of SFRC. There are mainly two different approaches that can be found in literature. A first method is based on the principles of the inverse analysis procedure, in which the non-linear tension softening behaviour of SFRC is estimated by a curve fitting-algorithm [1–3]. The second method to model the post-cracking residual tensile capacity of SFRC takes into account the individual pull-out behaviour of a fibre (either numerically [4,5] or analytically [6,7]). This way of modelling has a large advantage with respect to the first one because the amount of fibres that cross a crack as well as the distribution and orientation of fibres can be used as input parameters to predict and to simulate the residual tensile strength of concrete.

When the experimental pull-out behaviour was used as a basis for the prediction of uni-axial or bending behaviour of SFRC by Cunha et al. [6] and Armelin et al. [4,5], they had to divide the orientations of fibres in relatively wide discrete intervals. This led inevitably to a less accurate prediction of the real composite behaviour. Moreover, the obtained experimental pull-out data

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Table 1
Bending tensile strength $f_{ct,fl}$, compressive strength f_c and density of normal (N) and high strength (H) mortar at 28 days.

Mortar type	$f_{ct,fl}$ (N/mm^2)	f_c (N/mm^2)	Density (kg/m^3)
N	7.55	47.4	2170
H	9.47	76.5	2190

was only useful to model the bending behaviour of prisms which were made of the same fibre type and concrete. In order to improve the pull-out-based approaches and to make it more acceptable to other researchers, a generally applicable model to predict the pull-out behaviour of hooked-end steel fibres is necessary and is proposed in this work.

First successful attempts to model the pull-out response of hooked-end steel fibres were made by Alwan et al. [8] and Chanvillard [9]. However, their approaches are quite different: while Chanvillard used the principles of virtual work and divided the hook into distinct curved and straight parts, Alwan modelled the hook as two discrete hinges and presented the pull-out curve as a chain of different parabolas. More recently, Laranjeira [10] and Ghoddousi et al. [11] proposed new models which are quite comparable to the model developed by Alwan et al. [8]. A main advantage however of the model developed by Laranjeira et al. [10] is the possibility to deal with a variation in pull-out inclination.

An experimental programme has been conducted, dealing with varying physical parameters such as mortar compressive strength, fibre tensile strength, fibre orientation, fibre embedded length, fibre diameter and shape of the hooked end. A first series of tests on straight fibres were carried out to determine physical parameters of the fibre/matrix interface in the debonding phase of the pull-out process. These parameters are then used to model the debonding of the straight part of the hooked-end steel fibres. A second series of pull-out tests were carried out on fibres with hooked ends to investigate the effect of the additional mechanical anchorage on the fibre pull-out behaviour.

Based on the experimentally obtained results and the principles of virtual work as explained by Chanvillard [9], a semi-analytical model is proposed to describe and to quantify the individual fibre pull-out behaviour by means of a load-slip relation. The developed model is, with respect to the more recent pull-out models [10,11], generally applicable for a wide range of hooked-end fibre types in combination with different concrete qualities. It describes the debonding process of both straight and deformed parts of the fibre and it includes the additional anchorage due to the plastic deformation of the hook. The proposed model is validated by experiments and it is used to determine the critical physical properties and orientation angle for the occurrence of fibre rupture. The major part of this paper is based on the PhD thesis of the second author [12].

2. Experimental investigation

2.1. Specimens

The aim of the experimental programme is to study the influence of mortar strength, fibre type, orientation and fibre embedded length. Therefore, two different mortar strengths (Table 1), four different fibre types (Table 2, Fig. 1), five different fibre orientations angles θ (0°, 15°, 30°, 45°, 60°) and two different fibre embedded lengths L_E (10 and 30 mm) were considered.

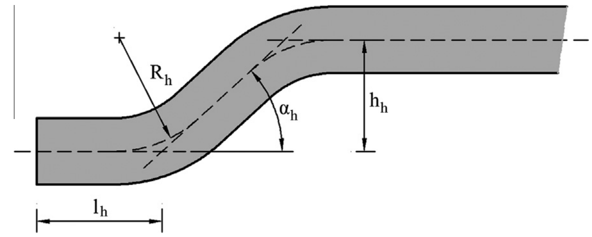

Fig. 1. Geometrical properties of the hooked-end.

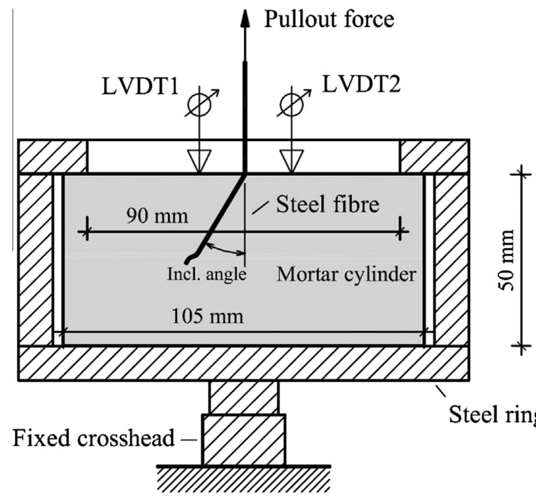

Fig. 2. Schematic of the test setup.

In each mortar cylinder, one steel fibre was placed in a fixed position (Fig. 2). A combination of two different fibre diameters (0.50 and 0.80 mm) and two different steel qualities, related to a low (LC) and high (HC) carbon content, resulted in the use of four different fibre types. The ultimate tensile stress was determined by means of an axial tensile test conducted on individual fibres. For each type of fibres, the end-hook geometry, the mean fibre tensile strength f_y and both fibre length l_f and diameter d_f are given in Table 2. The values of l_h, R_h, h_h and α_h are measured as shown in Fig. 1.

All test series were given a unique designation, which consists of three parts. The first part is a combination of three letters: N or H for normal or high strength mortar; L or H for low or high carbon content (high or ultra-high fibre tensile strength) of the fibre; and S or H for straight or hooked-end fibres. The second part is a combination of three numbers: the first number is the fibre diameter expressed in one hundredths of a millimetre, the second denotes the embedded length in mm and the last one denotes the inclination angle (in degrees) of the pull-out force direction. This pull-out inclination angle is measured between the fibre axis and the perpendicular to the concrete surface. For example, the test which has the code NLH 50-10-30 is a specimen made of normal strength concrete with a low strength hooked-end fibre. The fibre has a diameter of 0.50 mm, the total embedded length is 10 mm and the inclination angle is equal to 30°. In total, 120 (three specimens in each test series) mortar cylinders with a height of 50 mm and a diameter of 105 mm were cast. After casting and compaction on a vibration table, the mortar cylinders were stored at 20 °C and a RH of 95%. One day after casting, the specimens were demoulded and restored at initial curing conditions until they were tested at the age of 28 days. An overview of the experimental testing programme is given in Table 3.

2.2. Test setup

Regarding the large number of different test setups that can be found in literature [13–20], the pull-out test setup was chosen in order to simulate as much as possible the real situation of a random fibre in a cracked composite. This implies

Table 2
Geometric properties of the hooked-end, fibre tensile yield strength f_y, total length l_f and diameter d_f.

Fibre type	l_h (mm)	h_h (mm)	α_h (°)	R_h (mm)	f_y (N/mm^2)	l_f (mm)	d_f (mm)
ZC 50/.50 LC	2.22	1.95	60	0.92	1345	50	0.50
ZC 60/.80 LC	2.04	1.65	50	1.29	1215	60	0.80
ZC 50/.50 HC	1.95	1.51	41	1.26	2148	50	0.50
ZC 60/.80 HC	1.87	1.98	50	1.16	2117	60	0.80

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