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Predicting pull-out behaviour of 4D/5D hooked end fibres embedded in normal-high strength concrete

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ABSTRACT

Previous research (Abdallah et al., 2016) conducted by the authors had proposed an analytical model to predict the pull-out behaviour of 4DH/5DH fibres embedded in ultra-high performance concrete. The present paper is an extension to the prior study and focuses on the pull-out load-slip behaviour of these fibres embedded in normal-high strength concrete combinations. Based on experimental investigations, an elastic-plastic moment expression has been proposed to represent the partially plastic hinge formed during pull-out of each circular steel fibre. This prediction takes into account the variation of concrete strength, geometrical and tensile properties of the fibres. Partial deformation in straightening of the hook as well as fibre rupture was also included in the analysis. The model developed is validated against experimental pull-out results of various hooked end fibres, for which reasonable to very good predictions are found.

1. Introduction

Steel fibre reinforced concrete (SFRC) has become increasingly used in modern structural engineering applications [2]. It is well established that short steel fibres, when added to cementitious materials, improve their tensile response, ductility, energy absorption and crack resistance [3–5]. Another main advantage of fibre reinforcement is to enable the concrete to persist in carrying load after cracking, the so called post-cracking behaviour [6,7]. The effectiveness of fibre in transferring stress from the matrix is dependent on the bond mechanisms that apply to the fibre/matrix interface [8–10].

The bond refers to the mechanism through which the applied tensile force is transmitted between the steel fibres and the surrounding cementitious matrix [11]. A part of this force is resisted by the cementitious matrix, whilst the remainder is resisted by the fibres. The tensile strength of SFRC can be quite variable, depending mainly on the fibre/matrix bond strength. For the case where the fibres have a weak bond to the matrix, pull-out at low loads is likely to occur and thus the fibre does not contribute much to resisting the propagation of cracks [12]. Conversely, if the bond is too strong, the fibre may rupture before it can contribute fully to the post-crack strength. Therefore, an understanding of bond mechanism is a key factor to controlling the mechanical properties of SFRC [13]. Currently, pull-out tests upon a single fibre are used to investigate the bond characteristics at the interface [14].

Steel fibres for the use in concrete reinforcement can be categorized into deformed and undeformed types. The latter (i.e. straight) fibre is rarely used in practice and almost all fibres commercially available today are mechanically deformed in their original geometry [15,16]. These deformations apply either to the fibre ends, such as hooks, paddles, and buttons or to the fibre length, such as indented, crimped and polygonal twisted fibres [17]. Of these, the hooked end fibre of single bend has been the most widely used compared with other types [18]. Recently, hooked end steel fibres of improved shape were introduced, namely, 4D (double bend) and 5D (triple bend) hooked ends. These fibres are designed to increase the anchorage capacity of a concrete structure to bear complex loading including tension, compression and shear [19].

The higher performance need is matched to a multi-bend hook in a refined matrix. The two-bend hook and traditional matrix material are suitable for many applications where the requirement for a certain load of safety is ensured. Should that level be sacrificed, say, in favour of a minimum weight design, the hooked end fibre can be expected to bridge tensile cracking in the matrix until the fibre force attains its pull-out limit. The latter would be chosen for the hook geometry and matrix quality from the various combinations available. The greatest pull-out force deems that a bend pull attains 100% plasticity across the fibre section when both the steel and the concrete are at their strongest [1]. Lesser pull-out forces spread less plasticity in normal-medium strength combinations where slip is facilitated by a crushing failure at the fibre/matrix interface. The pull-out force theory has adopted two alternative

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Table 1
Mix design of mixtures.

Concrete type	Mix proportions (kg/m³)						W/B	Compressive strength
	Cement (type)	Fly ash	Aggregates	Sand	Superplasticizer	Water	(–)	(MPa)
			8–10 mm	0–mm				
NSC	364(32.5R)	–	979	812	–	200	0.55	33
MSC	350(52.5 N)	107	660	1073	–	205	0.45	54
HSC	480(52.5 N)	45	850	886	6	210	0.40	72

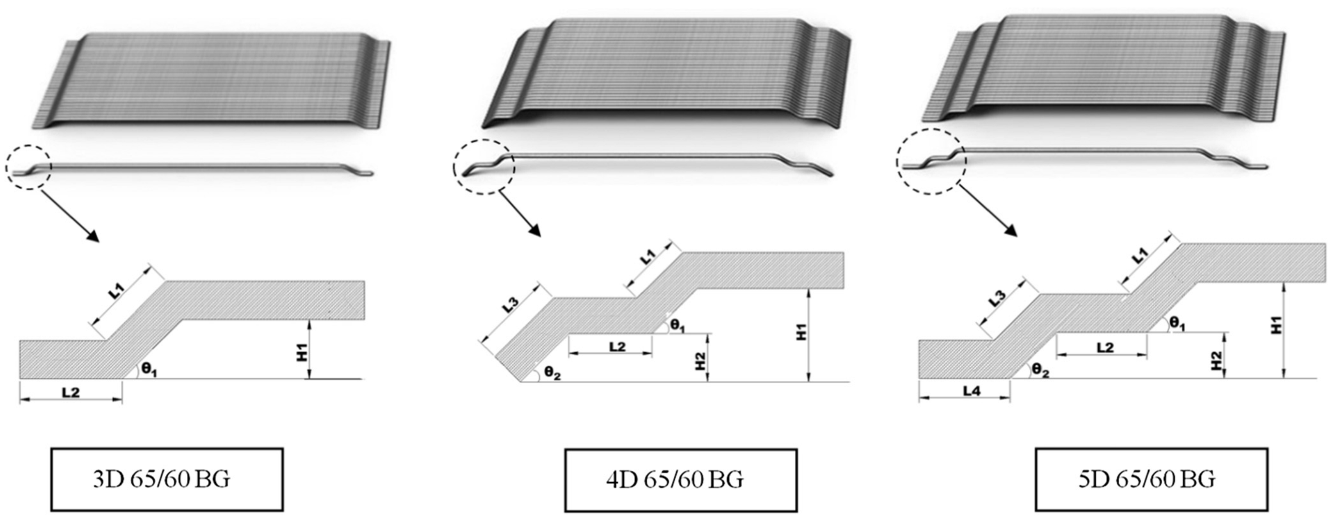

Fig. 1. Geometrical properties of hooked end steel fibres.

approaches. The first uses the equations of static force and moment equilibrium [1,20] and the second adopts the principle of virtual work [21,22]. Both admit both static and dynamic friction in which slip occurs under a critical force that surpasses the fibre's limiting elastic force. The maximum pull-out force is attained in overcoming the frictional bond from matrix contact and in straightening the hook to initiate a continuous slip. With a broken bond slip continues under a reduced pull-out load required only to oppose the dynamic friction.

The present paper examines those fibre-matrix conditions for a pull-out force where a full straightening of the fibre is not observed. The elastic-plastic moment expression is assumed to accommodate the plastic penetrations of 30, 50 and 70% of the fibre sectional area. The model, when compared to alternative moment expressions, is validated against experimental results for all three hooked end fibres embedded in normal-high strength concretes. This study is necessary in order to predict more reliably the pull-out behaviour of hooked end fibres for various fibre geometries and concrete strengths.

2. Experimental investigation

2.1. Materials and specimens preparation

Three different concrete grades namely, normal strength concrete (NSC), medium strength concrete (MSC) and high strength concrete (HSC) were included in the experimental programme. The NSC mix design was prepared using ordinary Portland cement (i.e. CEM II 32.5R) whilst the other two mixes all employed high strength Portland cement (CEM III 52.5N). Fly ash, washed sea sand as the fine aggregate and crushed granite having a maximum size of 10 mm as coarse aggregates were also used for the preparation of the NSC, MSC and HSC mixtures. A superplasticizer called TamCem 23SSR was used for the preparation of the HSC mixture. The detailed mix proportions used in this study are summarized in Table 1.

Three types of commercially available hooked end steel fibres, namely Dramix 3DH, 4DH and 5DH, were used in the pull-out tests. These fibres have a same length (60 mm), diameter (0.9 mm) and aspect ratio ($l/d = 65$) and only differ in the hook geometry and tensile strength. The geometrical properties of these fibres are depicted (stacked) in Fig. 1 and detailed in Table 2. To determine the fibre/matrix interface characteristics, straight fibres (i.e. 3DS, 4DS, and 5DS)

Table 2
The measured geometric and mechanical properties of hooked-end fibres.

Fibre type	σ_u [a] (MPa)	σ_y [b] (MPa)	l_f (mm)	d_f (mm)	Hook length (mm)				Hook angles (°)			Hook height (mm)	
					L1	*L2*	*L3*	*L4*	θ_1	θ_2	β	H1	H2
3D 65/60 BG	1150	1100	60	0.90	2.12	2.95	–	–	45.7	45.5	67.5	1.85	–
4D 65/60 BG	1500	1400	60	0.90	2.98	2.62	3.05	–	30.1	30.8	75.0	4.37	2.20
5D 65/60 BG	2300	2150	60	0.90	2.57	2.38	2.57	2.56	27.9	28.2	76.0	2.96	1.57

[a] Ultimate strength.
[b] Yield strength.