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# Development of a generic three-dimensional finite element fibre pullout model

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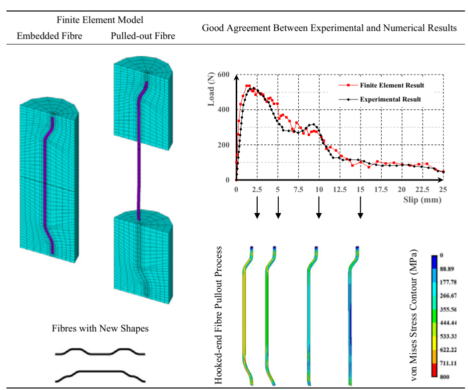
## HIGHLIGHTS

- A generic nonlinear finite element model for steel fibres pullout from concrete is proposed.
- The model captures debonding, frictional sliding, material plasticity, etc.
- Good agreement between the experimental and numerical results is achieved.
- The validated model is employed as a virtual laboratory unit to design new steel fibres.

## GRAPHICAL ABSTRACT

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## 1. Introduction

The main disadvantage of concrete under low confining pressure is its brittleness, i.e., relatively low tensile strength and ductility and poor resistance to crack opening and propagation. Therefore once cracking is initiated, concrete drastically loses its load carrying capacity in tension. This drawback which limits practical applications of plain concrete could be overcome by the inclusion of a small amount of discontinuous and short steel fibres which are randomly distributed within the concrete. This composite material is generally known as Fibre Reinforced Concrete (FRC) [1,2].

Among all the common fibre materials, steel is the most suitable for structural purposes [1]. In the early days of Steel Fibre Reinforced Concrete (SFRC), the fibres were mostly undeformed (straight) [3]. The crack bridging performance of such fibres directly depends on the physical and chemical adhesions between the fibres and the surrounding matrix (physicochemical bond) which are predominantly determined by the properties of the fibre-matrix interface and matrix packing density [4]. More recent research indicates that the mechanical anchorage in the deformed fibres effectively improves pullout resistance [3,5,6]. The mechanical bond properties are determined by the physical geometry of the fibre and the transverse tensile strength of the matrix. The mechanical anchorage could be provided by deformation at the fibre ends, such as with hooked-end fibres (which locally increases the mechanical bond), or deformation along the fibre length, such as in crimped or twisted fibres (which provides a mechanical bond along the fibres) [4]. Typical steel fibres are shown in Fig. 1.

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**Notations**

| | |
|---|---|
| $c$ | contact cohesion, MPa |
| $d$ | decay coefficient |
| $E_c$ | Young's modulus of concrete, GPa |
| $E_s$ | Young's modulus of steel, GPa |
| $E_t$ | total dissipated pullout energy, Nm |
| $f_{ck}$ | characteristic cylinder strength of concrete, MPa |
| $f_{ctm}$ | mean tensile strength of concrete, MPa |
| $f_n$ | normal component of contact force, N |
| $f_t$ | tangential component of contact force, N |
| $f_u$ | ultimate stress of steel, MPa |
| $f_y$ | yield stress of steel, MPa |
| $F$ | force vector |
| $g_n$ | penetration along the normal direction, mm |
| $g_t$ | penetration along the tangential direction, mm |
| $k_n$ | normal penalty stiffness, N/mm |
| $k_t$ | tangential penalty stiffness, N/mm |
| $K_b$ | stiffness matrix of the contacting bodies |
| $K_c$ | contact stiffness matrix |
| $l_{em}$ | embedded length, mm |
| $P_{max}$ | maximum pullout load, N |
| $u$ | displacement vector |
| $\varepsilon_u$ | ultimate strain of steel |
| $\mu$ | frictional coefficient |
| $\mu_d$ | dynamic coefficient of friction |
| $\mu_s$ | static coefficient of friction |
| $\upsilon$ | slip rate, mm |
| $\upsilon_c$ | the Poisson's ratio of the concrete |
| $\upsilon_s$ | the Poisson's ratio of the steel |
| $\rho$ | normal contact pressure, MPa |
| $\tau$ | equivalent shear stress, MPa |
| $\tau_{max}$ | maximum shear stress, MPa |

The evaluation of post-cracking response has main importance for SFRC composites to be effectively and economically employed in practice. The residual post-cracking tensile strength of conventional SFRC is directly related to both fibre volume content (specifically the amount of fibres crossing a crack) and the fibre-matrix interfacial bond characteristics. Although such characteristics are best described by a bond-shear-stress-slip relationship, the direct experimental determination of such a relationship has not yet been possible. However, a load versus slip response which can be obtained from the fibre pullout test is employed by researchers to study the characteristics of the fibre-matrix interface [7–9].

The structural contribution of such material mainly depends on its tensile/flexural characterisation. Currently there is no standard direct tension test for fibrous concrete mainly because it is difficult to provide a proper gripping arrangement to avoid specimen cracking at grips. On the other hand, bending test is a widely used test method for performance evaluation of SFRC [10].

Analytical procedures can be employed to correlate the pullout response of individual fibres with the overall direct tensile and flexural performances of SFRC specimens where the fibre inclination, embedment length, and fibre density distribution are taken into account [11,12]. For instance, Armelin and Banthia [11] developed a model based on simple principles of mechanics to estimate the flexural response of SFRC prisms. The pullout load-slip relationship of single fibres at different angles of inclination and the compressive strength of the matrix are the input parameters of the model. Furthermore, there are closed-form formulations presented in the literature to back-calculate constitutive material behaviours in compression and tension from flexural test result. The constitutive material models are required in the design of structural members [13–15].

Therefore, the knowledge of the single fibre pullout behaviour is essential to understand the uniaxial or bending behaviour of SFRC composites.

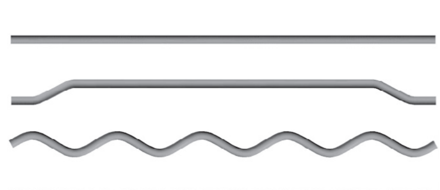


**Fig. 1.** Types of steel fibre.

The fibre-bridging-pullout process is a sophisticated mechanism which consists of cohesion, interfacial debonding, sliding frictional contact, fibre deformation and material plasticity. Since the introduction of steel fibre, numerous research studies have been conducted to investigate the pullout mechanism of such fibres interacting with concrete. However, limited research has been carried out using Finite Element (FE) and analytical methods, while the majority of the investigations were conducted experimentally [3,4,6–9,16–19].

An analytical model of the entire pullout process for smooth steel fibres was developed by Naaman et al. [18] where a bond-stress-slip relationship of the interface with decaying behaviour capability was incorporated in the model to capture the descending branch of the pullout response. The effect of hook deformation as the mechanical anchorage on the pullout mechanism of steel fibres was advanced by Van Gysel [20,21] using the principle of energy conservation. The investigation was based both on theoretical and experimental considerations where fibre debonding, plastic deformation, and additional frictional force due to incomplete straightening of the hook was taken into account. Alwan et al. [22] presented an alternative approach using the concept of the frictional pulley to simulate the hook action. The model consists of two frictional pulleys which have rotational and tangential components of friction resisting the pullout process. The components respectively correspond to the work required for the fibre straightening and friction between the fibre and matrix in the curved duct. Sujivorakul et al. [23] employed the concept of nonlinear springs to simulate the effect of the hook. The approach superposes the effect of the spring on the previously proposed pullout models for straight fibres by applying an iterative procedure over the geometry of the mechanical anchorage. A model to predict the pullout of mechanically deformed steel fibres from concrete was developed by Zīle and Zīle [9] based on the law of conservation of energy. The increase in the pullout load caused by mechanical anchorage depends on the amount of plastic work required to straighten the fibre during pullout. The model predictions were compared with experimental pullout results of the hooked-end and crimped steel fibres where good agreement was observed.

In addition, there are other analytical investigations focused on the pullout behaviour of fibres embedded in concrete with varying inclinations respect to the loading direction. In this case, the fibre-matrix interaction at the point where fibre exits the matrix, i.e. exit point of fibre, becomes highly complex. These pullout scenarios better represent the ones existing in practical applications, where random orientation of fibres is likely to occur. Laranjeira et al.