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Influence of fibre orientation on the tensile behaviour of ultra-high performance fibre reinforced cementitious composites

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ABSTRACT

The main objective of this study is to quantify the effect of fibre orientation on the tensile behaviour of Ultra-High Performance Fibre-Reinforced Cementitious Composites (UHPFRC). A strategy to align the steel fibres within the matrix based on the activation of an external magnetic field while casting is adopted to achieve a wide range of fibre orientation profiles. The uniaxial tensile test is used for determining the tensile stress-elongation curves of 22 specimens and the quantitative evaluation of the fibre density and orientation characteristics is performed resorting to an image analysis technique. Based on the obtained results it was possible to validate an analytical formulation for determining the tensile strength of UHPFRC and to quantify the involved parameters. It is also shown that length of the hardening branch of the tensile stress-elongation curve is also very well correlated with the same parameters used in the determination of the tensile strength.

1. Introduction

Ultra-high performance fibre reinforced cementitious composites (UHPFRC) designate a family of advanced cementitious materials with enhanced matrix packing density, very low water/binder ratio ($w/b < 0.2$), and containing a significant amount of high strength short steel fibres [1,2]. This combination provides superior performances in terms of compressive strength, energy absorption capacity, ductility and durability [3–5]. One of the main advantages of adding short steel fibres in an ultra-high performance matrix is tensile behaviour improvement, since the fibres are able to transfer stresses across the crack surfaces.

The tensile response of UHPFRC with high fibre contents is characterized by an initial elastic branch followed by strain hardening accompanied by the formation of a stable micro-crack pattern up to the peak stress. This tensile hardening behaviour may be a requirement for specific structural applications. After the peak-stress, strain-localization occurs in the form of a macro-crack with large energy dissipation capacity prior to complete stress release [6]. Fig. 1 shows a schematic representation of the uniaxial tensile stress – elongation response of UHPFRC. In this figure, E_U is the elasticity modulus of the composite, f_{Ute} and ε_{Ute} are the notional matrix cracking stress and strain, f_{Utu} and ε_{Utu} are the (post-cracking) tensile strength and corresponding tensile strain, g_f is the energy dissipated per unit volume, E_{Uu} and ε_{res} are the elasticity modulus and the residual strain at unloading, and G_f is the energy dissipated in the post-peak stage per unit surface area of the macro-crack.

The behaviour described above is governed by the fibre characteristics (geometry and aspect ratio), fibre-to-matrix bond, and fibre distribution and orientation [7–11]. If the formers can be tailored during mix design, the distribution and orientation of the fibres are influenced by the rheology of the composite in the fresh state, mixing and placing procedure, geometry and dimensions of the specimen, and wall-effects [9,12]. Considering all these influences, preferential fibre orientation along a given direction is likely to occur within a UHPFRC element. Since the effectiveness of the fibres depends on their orientation with respect to the acting principal tensile stresses, this leads to an anisotropic tensile behaviour which needs to be characterized.

The uniaxial tensile behaviour of UHPFRC can be experimentally assessed using the uniaxial tensile test (UTT) for which a variety of test setups and shapes for the test specimens can be found in the literature [4,6,13–16,38]. However, due to the relatively narrow width of most of the test specimens, the fibres are usually well oriented towards the direction of the applied stress. Therefore, the obtained tensile properties may not be representative of those found in a real structure [7,17] and can be somehow overestimated. This issue is being addressed in recent research [40]. Given that most UHPFRC mixes are self-compacting, some works were developed aiming at quantifying the effects of the flow induced orientation on the tensile behaviour of UHPFRC. The different fibre orientation profiles were achieved either by adopting suitable casting methods for the small-scale laboratory specimens [18–22] or by extracting specimens from large UHPFRC slabs oriented at different directions with respect to the flow of the material while casting [7,

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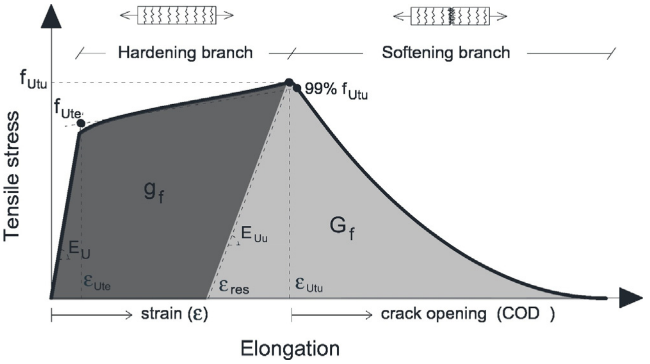


Fig. 1. Schematic representation of the tensile behaviour of UHPFRC exhibiting strain hardening in tension.

17,23]. However, it is worth noting that in most of the mentioned researches either the range of the fibre orientation profiles remained limited or the tensile behaviour was characterized using indirect tests, not providing quantitative information about the influence of the fibre orientation on the uniaxial tensile strength nor on the development of the tensile hardening branch. Therefore, experimental evidence regarding the influence of fibre orientation on the uniaxial tensile response of UHPFRC for a wide range of fibre orientation profiles is still needed.

In a previous work, Pimentel and Nunes [24,25] used the double-edge wedge splitting (DEWS) test [26] to estimate the post-cracking uniaxial tensile strength of UHPFRC specimens produced with a very wide range of orientation profiles. The orientation of the steel fibres was achieved through the activation of a magnetic field while casting the specimens. Although the DEWS test provides good estimates of the post-cracking uniaxial tensile strength f_{Utu} of the composite, no quantitative information regarding the remaining fracture parameters could be obtained. In the work presented herein, the previous experimental campaign is extended and the uniaxial tensile test is used so that the effect of fibre orientation on all the tensile fracture parameters shown in Fig. 1 can be quantitatively assessed, both in the hardening and softening stages. An image analysis technique is employed in all the tested specimens to determine the fibre orientation distribution and to quantify the relevant parameters of an analytical formulation [27] to estimate tensile strength of fibre reinforced composites.

2. Model to estimate tensile strength of UHPFRC

The tensile strength of UHPFRC, f_{Utu}, is normally governed by fibre debonding followed by fibre pull-out, the latter marking the onset of the softening stage. Assuming a rigid-plastic law during the debonding stage for the fibre-to-matrix bond stress – slip relationship and an average fibre embedded length of $l_f/4$, the tensile strength of UHPFRC can be determined as follows [27]:

$$f_{Utu} = \alpha_0 \alpha_1 \tau_f V_f \frac{l_f}{d_f} \tag{1}$$

where, α_0 is the fibre orientation factor, α_1 is the fibre efficiency factor, τ_f is the equivalent rigid-plastic fibre-to-matrix bond strength, V_f is the fibre volume fraction, l_f and d_f are the length and diameter of the fibres, respectively.

The fibre orientation factor, α_0, is defined as the probability of a single fibre being intersected by a random section plane and is determined as follows [28]:

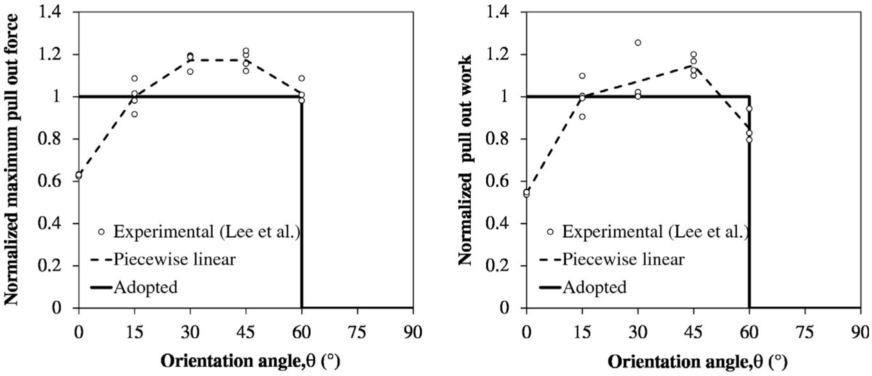
$$\alpha_0 = n_f \frac{A_f}{V_f} \tag{2}$$

where n_f is the number of fibres crossing a unit surface area of the plane and A_f is the cross-section area of a single fibre (for the fibres used in this research: $A_f = 0.024\text{mm}^2$). This is a scalar orientation indicator and is therefore associated to a direction in space, defined by the normal to the intersecting plane. It can be shown that if the fibres are assumed to be uniformly oriented in space, then $\alpha_0 = 0.5$ for any direction and the material is isotropic [29]. If the fibres are constrained to a planar distribution and still uniformly distributed, then $\alpha_0 = 2/\pi$ for any in-plane direction and the material is transversally isotropic [30]. In cases where the fibres are not uniformly distributed, for instance due to flow induced orientation and/or wall effects, the orientation factors in two orthogonal directions are inversely related that is, when one increases, the other must decrease, explaining the anisotropic structure of the material [7].

The fibre efficiency factor, α_1, is a parameter that accounts for the dependency of the fibre pull-out force with the orientation angle θ (i.e., the angle of the fibre with the normal to the fracture surface). The fibre efficiency factor is defined as the expected value of fibre efficiency function, $g(\theta)$:

$$\alpha_1 = \int_0^{\frac{\pi}{2}} g(\theta) f(\theta) d\theta \tag{3}$$

where $f(\theta)$ is defined as the probability density function of the orientation angle of the fibres intersected by the fracture plane, and is here established based on the analysis of high resolution images of polished surfaces parallel to the fracture plane. The fibre efficiency function $g(\theta)$ can be defined as the ratio between the pull-out force of a fibre oriented at θ and the pull-out force of an aligned fibre. A fibre is here considered as aligned (or well oriented) if it is oriented



(a) (b)

Fig. 2. Normalized maximum pull out force (a) and pull out work (b) of a single fibre as a function of the orientation angle (values normalized by the average pull out force or pull out work at 15°). Experimental data from Lee et al. [8].