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Modelling the influence of the fibre structure on the structural behaviour of flowable fibre-reinforced concrete

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ABSTRACT

This paper presents a modelling approach for fibre-reinforced concrete elements in which the fibre structure is taken into account in simulating the mechanical behaviour. The fibre structure is discretized in volumes and two fibre parameters are defined for each discrete volume: the dominant fibre orientation and the fibre volume fraction. These parameters are incorporated in a numerical model that uses a single-phase material definition dependent on the fibre parameters. The first part of this paper describes the methodology and constitutive modelling. The second part addresses the simulation of two beams that exhibited large differences in bending because of uneven fibre distribution. Data on the fibre structure was obtained using Computed Tomography scanning. The modelling approach captured the large difference in the flexural response of the two beams and provided an adequate prediction of the location and propagation of the critical cracks.

1. Introduction

Predicting the overall mechanical behaviour of a fibre-reinforced concrete (FRC) element usually requires the characterization of the post-cracking behaviour of the FRC. This is often determined either directly, in direct tension tests (e.g., RILEM [41]), or indirectly by performing inverse analysis of bending tests, splitting tests, or other indirect tension tests [1–5]. Inverse analysis of the test results makes it possible to determine the material tensile behaviour considering a certain stress-strain or stress-crack width relationship. Bi-, tri- and poly-linear functions are usually proposed in the literature to describe the post-cracking behaviour of FRC [4,6–14]. Several technical recommendations [15–18] also provide simplified formulations of the constitutive behaviour of FRC based on bending tests, which facilitate the material characterization for design purposes.

The post-cracking behaviour of FRC in a structural element, especially if it is flowable or self-compacting FRC, can differ from the post-cracking behaviour of a test specimen. The rheological properties, the casting procedure, and the structural geometry can lead to an uneven fibre structure in the element, meaning inhomogeneity of the fibre volume over the length or depth of the element and a preferred alignment of the fibres [19–24]. In such cases, modelling the FRC as if it were a homogeneous material can lead to inaccurate results.

In an attempt to take into account its fibre structure, FRC can be modelled as a two-phase material [25–27], where the concrete matrix is described as a homogeneous material, while the fibres are treated explicitly as discrete entities. This approach has the advantage of directly including the effect of fibre location and orientation, but requires a definition of the concrete matrix model, the fibre model, and the interface model for the fibre-matrix bond response. This response is often based on results from pull-out tests of single fibres and/or analytical expressions that include effects such as the fibre embedded length, fibre inclination, or the anchorage of the fibre end [28,29]. It is commonly assumed that fibres do not interact with neighbouring fibres, but when a large fibre dosage is used, failure mechanisms can be interactive, creating a collective failure that cannot be captured by describing the failures of individual fibres [28,30].

The current paper presents a modelling approach for analysing FRC structural elements in which the fibre structure is modelled by assuming volume-wise constant material properties. Since the material cannot be assumed to be homogeneous on the scale of the structural element, a spatial discretization of the element is defined within which the material can be considered homogeneous. The process consists of (see Fig. 1): (i) obtaining the fibre structure, (ii) discretizing the structural element in volumes, (iii) determining the fibre structure properties within each discrete

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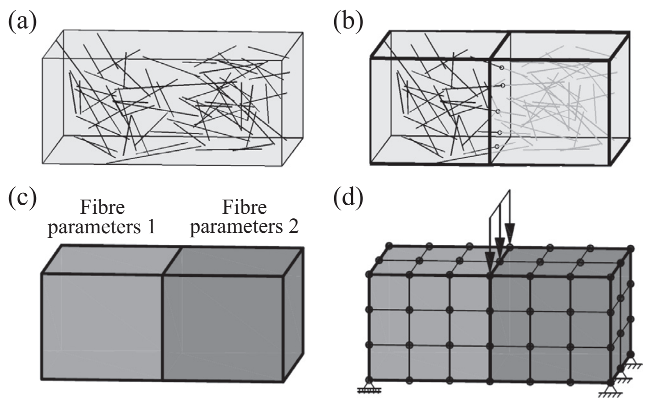

Fig. 1. (a) Matrix and fibre structure, (b) discretization in volumes, (c) homogenization within discrete volumes and (d) finite element model.

volume, (iv) defining an adequate constitutive model that describes the behaviour of the FRC at the discrete volume level making use of the fibre structure properties, and finally, (v) simulating the structural response using finite element (FE) modelling.

The constitutive model (iv) is applied at an intermediate level which is between the fibre level and the structural element level. It uses a single-phase material definition, with the consequent computational advantages for application to structural elements. In this way, the definition of the matrix-fibre interface behaviour is circumvented. However, a new issue is raised. As already mentioned, single-phase material models for FRC are commonly calibrated by inverse analysis of test results at the scale of test specimens. Such an approach is not feasible for the intermediate level. Since the focus of this research was on the modelling approach as a whole (i–v) and in the absence of a well-established constitutive modelling technique for this intermediate level, heuristic assumptions were used for the constitutive modelling.

2. Modelling approach

Starting from a complete characterization of the fibre structure, this section describes the modelling steps that result in the proposed constitutive model for FRC for use at the discrete volume level. The section ends with an illustration of the constitutive model for various fibre structure parameters.

2.1. Fibre parameters within a discrete volume

In the present investigation, fibre structure properties were derived from a complete characterization of the fibre structure in which the precise position of every fibre is known. Several methodologies can be utilized for assessing the fibre structure of an FRC element, including flow simulations [31], numerical algorithms based on probabilistic distributions [26], X-ray Computed Tomography (CT) [20], and visualization of fibres within a viscous transparent fluid [32].

To define the local fibre properties, a discretization of the structural element in volumes was considered. The discrete volume size had to take into account criteria related to the size of the fibres and be sufficiently descriptive of the inhomogeneities of the fibre structure. Fibre properties were determined considering the fibres located in each volume. Because fibres can intersect one or several discrete volumes, the intersection points with the boundaries of the volumes needed to be determined. In this way, each segment of a fibre is considered in the volume in which it is located (Fig. 1b). Intersection points were obtained by assuming that fibres are perfectly straight.

This model incorporates the information from the spatial distribution of the fibres which can potentially influence the mechanical performance of a flowable FRC element, namely the fibre orientation and the local fibre content. The fibre orientation pattern of a body can be described using a set of second-order orientation tensors [23,33–35] defined over a set of discrete volumes of the body. Each orientation tensor describes the fibre orientation state within the volume and can be defined as:

$$\mathbf{A} = \frac{\sum_n L_n \mathbf{p}_n \mathbf{p}_n^T}{\sum_n L_n} \tag{1}$$

where $\mathbf{A}$ is the orientation tensor of a discrete volume. For all the fibres and fibre segments in the volume, $\mathbf{p}_n$ is a unit vector in the fibre direction, and L_n is the length of the fibre or fibre segment. By definition, the orientation tensor has the properties of being symmetric and having normalized components. Symmetric second-order tensors can be visualized using ellipsoids, where the eigenvectors, $\mathbf{a_i}$, and eigenvalues, λ_i, give the direction and half-length of the principal axes of the ellipsoids. In this way, ellipsoids are used as a visual tool to identify the dominant direction of the fibres in each discrete volume.

The second aspect, the local fibre content, is expressed in terms of volume fraction (v_f) and can be computed for each discrete volume as:

$$v_f = \frac{\sum_n L_n A_f}{V_c} \tag{2}$$

where A_f is the fibre cross-section area and V_c the discrete volume. The procedure described here makes it possible to represent the orientation and distribution pattern of a structural element by choosing a certain discretization of the element in volumes and assessing the fibre parameters $\mathbf{A}$ and v_f within each discrete volume. This is illustrated in Fig. 2 for the example shown in Fig. 1a.

2.2. Definition of fibre efficiency

When a crack arises, the efficiency of a fibre that bridges the crack depends on its orientation with respect to the crack plane. This can be expressed by the angle θ between the direction normal to the crack plane ($\mathbf{n}$) and the fibre direction. In a similar manner, it can be assumed that the efficiency of a group of fibres depends on the angle between $\mathbf{n}$ and the dominant fibre direction of the group of fibres. For the group of fibres (or fibre segments) in each discrete volume, the dominant fibre direction is given by the eigenvector associated with the largest eigenvalue of the orientation tensor ($\mathbf{a_1}$). The angle with respect to the crack plane may therefore be formulated as:

$$\cos\theta = \mathbf{a_1} \cdot \mathbf{n} \quad (\|\mathbf{a_1}\| = \|\mathbf{n}\| = 1) \tag{3}$$

Fig. 3 depicts two fibre orientation states represented by ellipsoids and illustrates the relevance of the variable $\cos\theta$ as a measure of fibre efficiency.

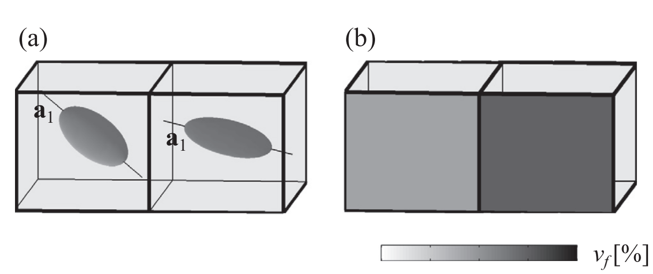

Fig. 2. (a) Orientation ellipsoids and dominant fibre orientation and (b) fibre volume fraction.