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Determination of steel fibres distribution in self-compacting concrete beams using X-ray computed tomography

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ABSTRACT

In this paper a study concerning an automatic determination of distribution of steel fibres in self-compacting concrete (SCC) is presented. The determination of fibre distribution is required to assess any relationship between those features and casting methods of concrete elements. Concrete beams with steel fibres of various types and casting methods were examined. Involved methods were computed tomography imaging followed by image analysis. After image analysis a label map consisting of all detected fibres was obtained, from which position and orientation in 3D of each fibre was calculated. The fibre distribution analysis was performed. The angles between the fibres and the beam main axis were examined. Statistical data analysis was performed that showed that the fibres' angles exhibit exponential distribution. Graphical visualization using 4D spherical histograms for quick assessment of fibres orientation is also presented.

1. Introduction

Nowadays, the widespread use of steel fibre reinforced concrete is observed, owing to ease of casting, while preserving the mechanical properties of typical steel-reinforced concrete. To utilize this method/material fully, its mechanical properties have to be known. Those depend greatly on the position and orientation of fibres within the casted element [1–3]. Finding the dependence of casting methods and composition on fibre orientation, and finally, on mechanical properties is a subject of continuous research [4–7].

The correlation between fibre distribution and fresh and hardened-state properties of steel fibre reinforced concrete (SFRC) also deserves deeper investigation, with regard to designing enhanced cement composites 'tailored' for specific structural applications [8–11].

A study [12] presents experimental works performed with the aim of analysing the orientation of fibres in different thin structural elements cast with steel fibre reinforced

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self-compacting concrete (SFRSCC). A slab, two walls and two 2.50 m long beams were studied, and the variation of fibre distribution and the consequent changes on the residual mechanical properties along these elements were discussed. These results show that the fibre distribution in SFRSCC structural elements varies with the flow rate and with the wall effect; the thickness of the elements or the proximity to the bottom of the moulds appears as important variables.

The early study has shown that the orientation of steel fibres within a SFRC structural element can be governed effectively through a well-balanced, fresh-state performance, as obtained by virtue of an appropriate mix composition, and a suitably designed casting process [13,14]. The aim of another paper [15] was to introduce, assess and compare several prototypes, based on inductive methods, created in order to determine the amount and orientation of the fibres, analysing their suitability as a systematic control method for SFRC.

The efficiency of short fibres in a composite material decreases from 100% when the fibres are all aligned along the major tensile stress to just 30%, when the fibres are randomly distributed [16–18].

The early use of a small-beam 150 mm × 150 mm cross-section, to evaluate the flexural behaviour of SFRC following the general guidelines [19], was analysed in [20], with the conclusions that the use of small beams can be particularly justified, when the specimen dimensions are more representative of the SFRC application, considering the effects of fibre distribution. The problem of describing the distribution steel fibres in the cross-section and along the length of the beam was analysed by Kamiński et al. [21] who built a simulation model of fibres distribution [22]. In the authors' opinion [23] the most significant is the fact that the method of calculating the geometrical characteristics of the cross-section for both the cracked and uncracked stage is based on the model of fibres distribution along the length of the beam.

The use of smaller beams may simplify the test and can be justified especially in SFRC for low height structural elements, considering the effects of fibre orientation [20–24]. It was found that the post-peak parameters of SFRC can be obtained using beams of smaller size when the fibre length and aggregate size are compatible with the dimension of the mould [20]. Even more important than the practical purpose is that they can be more representative, in order to evaluate SFRC to be used in thin slabs, concrete sheets, reinforcements or other low height structural elements, where a preferential orientation of the fibres may take place [20].

The distribution of the fibres inside the matrix is affected by a number of parameters, essentially: the geometry of fibres and their interaction effects (fibres-aggregates-formwork); the flowability of concrete; the means of pouring and compacting the concrete; and the geometry of the concrete shafts (free surface, two or four boundaries) and their dimension [4,25].

It is difficult to predict the fibre distribution state without doing sophisticated, destructive and/or non-destructive testing [26,27]. It is also important to determine the fibre distribution, considering separate fibre types and densities. Since the best concrete performance is expected when fibres are parallel to the beam's main axis [2,5,28], it is essential to determine the actual angle between them and analyse the obtained results, in terms of beams with various concrete parameters. Previous studies [13,26,29] about fibre-reinforced cement-based materials showed the effect of flow direction on the alignment and distribution of fibres. Short-cut discontinuous fibres had a tendency to align in the direction of flow, while the fibres in SCC tend to align themselves with the principal direction of flow, but mostly remain randomly distributed, perpendicular to this direction [17].

X-ray computed tomography (CT) imaging is a non-destructive method for obtaining a large number of consecutive sectional images of the internal microstructure of specimens of interest. It was used in several studies to characterize the engineering properties of cement-based materials in terms of parameters such as air-void space [30,31], spatial distribution of air content under axial loading [32], and clogging [33].

In the literature many methods proposed the evaluation of fibre orientation [27,34–36]. Overall orientation can be examined using AC inductive spectroscopy [37] which proved to be applicable on an industrial scale. Verification of the method was performed by analysis of cross-section images. The beam was cut and cross-sections were photographed. Using image-processing tools from the cross-section of each fibre due to its orientation could be calculated. A similar method requiring cutting of specimens is proposed in [16]. The main drawback of such an approach is that it cannot be applied on a larger scale owing to its time and labour requirements. A 3D image-processing approach using X-ray computed tomography was presented for the analysis of air voids [20], using generic image-processing software. The main idea of this approach can be easily adopted for the evaluation of steel fibre distribution in SFRSCC.

This paper presents an image-processing method for steel fibre distribution determination in 3D, using open-source C++ libraries for medical image processing. Section 2 discusses used materials and methods. Section 3 is devoted to statistical data analysis and results visualization. The paper ends with conclusions in Section 4.

2. Experimental program

2.1. *Materials and mix design*

The studies were performed on the SFRSCC with two types of steel fibre. The composition of the mix, where the proportions of the ingredients of the matrix are maintained and only the fibre content changes, is presented in Table 1. The concretes were prepared using water/cement ratios of all tested mixes equal to 0.41. The authors applied a high content of the cement (490 kg/m^3), which is widely investigated by other researchers [38–40]. The physical and chemical properties of cement CEM I 42.5R are presented in Table 2. The aggregate used in the mix was natural sand and coarse aggregate, with a maximum size of 2 mm and 8 mm, respectively. There were also two admixtures added: superplasticizer and stabilizer. The superplasticizer was based on polycarboxylate ether (concentration 20%) and characterized by density of 1.07 g/cm^3. The density of the stabilizer was equal to 1.01 g/cm^3. The superplasticizing admixture was dosed at 3.5% by weight of cement, in order to fit the slump flow range of 720–800 mm (see Table 4). The base constituent of the stabilizer was synthetic co-polymer. Both