POTENTIAL METHODS FOR QUALITY CONTROL OF FIBRE DISTRIBUTION IN FRC SCC

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ABSTRACT

In hardened concrete fibres aligned towards direction of tensile stresses work most efficiently. During the casting of fibre reinforced self-compacting concrete (FRC SCC) fibres tend to orientate in accordance with the flow. This property of FRC SCC can be used to achieve a desired orientation by optimizing the casting process and mix properties and thus minimizing the fibre content for a given load. If flow induced fibre orientation shall be applied in the industry, methods for quality control of fibre distribution in FRCSCC elements and structures are needed. Such methods should characterise fibre orientation, spatial distribution, and amount of fibres. In this paper an overview of potential methods for quality control of fibre orientation, distribution, and amount is given. Some experience of working with image analysis, manual counting and CT is also presented.

Keywords: fibre assessment; orientation; distribution

INTRODUCTION

It is known that fibres orientate with the flow of fresh concrete [1]. This phenomenon can be used to optimize the casting process so that fibres would orient towards desired direction. if this effect shall be used in industry there is a need for quality control methods that will detect the fibre orientation and concentration in certain parts of fibre reinforced concrete (FRC) elements. As the present literature survey shows, there are methods available which can be used to evaluate fibre orientation and distribution [2]. Moreover some of them have certain limitations or still need more development in order to be applied in practice [3-5].

FRC structure evaluation methods can be grouped into destructive and non-destructive methods [2]. Alternatively they could be grouped based on working principles as direct and indirect methods. The most interesting fibre distribution and orientation characterisation techniques are shown in (Cf.Tab.1).

Table 6. Fibre orientation and distribution assessment methods

Type	Method	
Direct	Manual counting of a number of fibres in a cut section	
	Image analysis	
	Computed tomography	
Indirect	AC impedance spectroscopy	
	Magnetic induction	
	Microwave imaging	Time domain reflection imaging
		Open ended coaxial probe imaging

A common feature for all the indirect methods is that they detect only conductive fibres, while direct methods can be used both for conductive and inconductive fibres. The disadvantage of AC impedance spectroscopy and microwave methods is their sensitivity to moisture content, while the magnetic probe method is not sensitive to these phenomena. The detailed description of each method can be found in the literature [2-8]. In this paper only direct methods will be described since they are used in our research on FRC.

DIRECT METHODS

Manual fibre counting is a simple method for fibre orientation and distribution quantification, as it doesn't require any special equipment or skills. If crushing FRC samples the fibre volume in the concrete can be estimated as well. As described in [9] it is possible to estimate fibre orientation by counting the fibre number crossing the cut surface (e.g. from slice of a beam) or fibre number can be obtained as an average from two parallel cut surfaces. By knowing the fibre number crossing the surface N_f, and assuming that the fibre amount v_f in the sample is the same as it was targeted in the mix design the orientation factor α in the current direction is calculated using equation(1).

$$\alpha = \frac{N_f \times A_f}{v_f \times A_C} \tag{1}$$

Where: A_f – area of the fibre cross-section, m^2; A_c – area of the cut concrete surface, m^2. Another way to estimate volume fraction of fibres v_f is based on assumption that all fibre orientations can be described as combination of three ideal possible orientations [9](equation(2)). For this purpose fibres are counted on three perpendicular surfaces of the prism (Cf.Fig.1).

$$v_f = \left(N_1 + \frac{9}{16} N_2 + \frac{7}{16} N_3 \right) \frac{A_f}{A_C} \quad (2)$$

Where: N1, N2, N3 are numbers of fibres crossing concrete surface.

Figure 7. Possible fibre orientations in the FRC element [9]

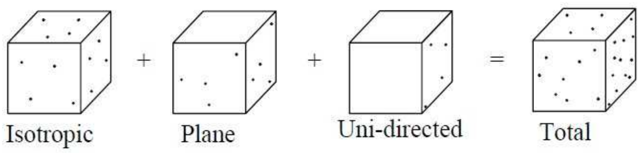


Image analysis is a widely used technique which gives possibility of fast evaluation of fibre distribution, fibre number or orientation on a given surface of fibre reinforced concrete with a help of a computer program. The image itself can be captured by various methods (like X ray imaging, SEM BSE, high resolution flatbed scanner [10, 11]). The image acquisition technique depends on fibre diameter and sample size. For fibre reinforced concrete where the fibre diameter is greater than 0.2mm, the sawn surface analysis seems to be most relevant from images taken with digital camera or flatbed scanner [11]. The use of digital camera doesn't require special equipment or skills and large fibre reinforced concrete slices can be photographed. In case where smaller diameter fibres are used other image acquisition techniques could be considered to obtain higher resolution (e.g. microscope imaging).

The fibre number N_f crossing an elements cross section can be related to its mechanical properties [1]. By comparing fibre number on different surfaces of a specimen fibre orientation and fibre volume fraction can be estimated (equation(2)). By knowing the total fibre number N_f crossing the region of interest and the volume fraction of fibres (from a concrete mix recipe) the fibre orientation factor α can be estimated [9, 12] (equation(1)).

The orientation of single fibre can be described using in plane (Φ) and out of plane (θ) angles (Cf.Fig.2). In order to calculate the out of plane angle using image analysis an ellipse is fitted to the fibre image. Therefore it is very important to have the sample surface polished before taking an image. This is necessary because the cutting process deforms the fibre tips, and because fibres which are in close distances become joined (Cf.Fig.2). This increases the error in determining the fibre number N_f and due to heavily distorted fibre edges it gives large errors in determining the fibre out of a plane angle. The out of plane angle θ is calculated using equation (3) below.

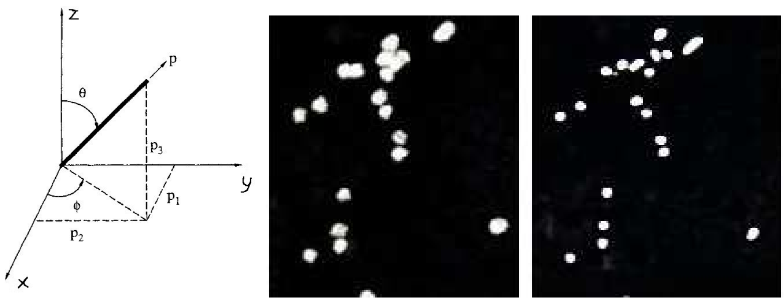
$$\theta = \arccos\left(\frac{b}{a}\right) \tag{3}$$

Where *a* and *b* are minor and a major axis of the ellipse shaped fibre cross section. To describe fibre orientation state for a number of fibres a more general description is needed. A tensor description method can be applied for fibre orientation density calculations [3]. The components of the orientation description tensor are calculated using equation(4).

$$a_{ij} = \frac{\sum\left(p_i p_j\right)_n \cdot F_n}{\sum F_n} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{xz} \\ a_{zx} & a_{zy} & a_{zz} \end{bmatrix} i, j = x, y, z \tag{4}$$

Where: a_{ij} - the components of the orientation tensor; p_x, p_y, p_z -give the orientation state of single fibre in reference directions by calculating projection length to x, y and z axis (Cf.Fig.2); *F* – is the weighting function to account the effect of fiber orientation on the probability of a fiber to cross the considered cross section; *n* – shows the number of fibres. If only the fibre number crossing the cut plane and distribution of the fibres are needed the time demanding polishing process can be skipped and replaced by the less laborious manual marking of each fibre position with a marker. This usually can be done faster than the polishing steps and no special equipment is required (for FRC samples with up to 2% of by volume of fibre dosage).

Figure 8. Orientation angles of a fibre[13], image of a FRC sample before polishing and after.

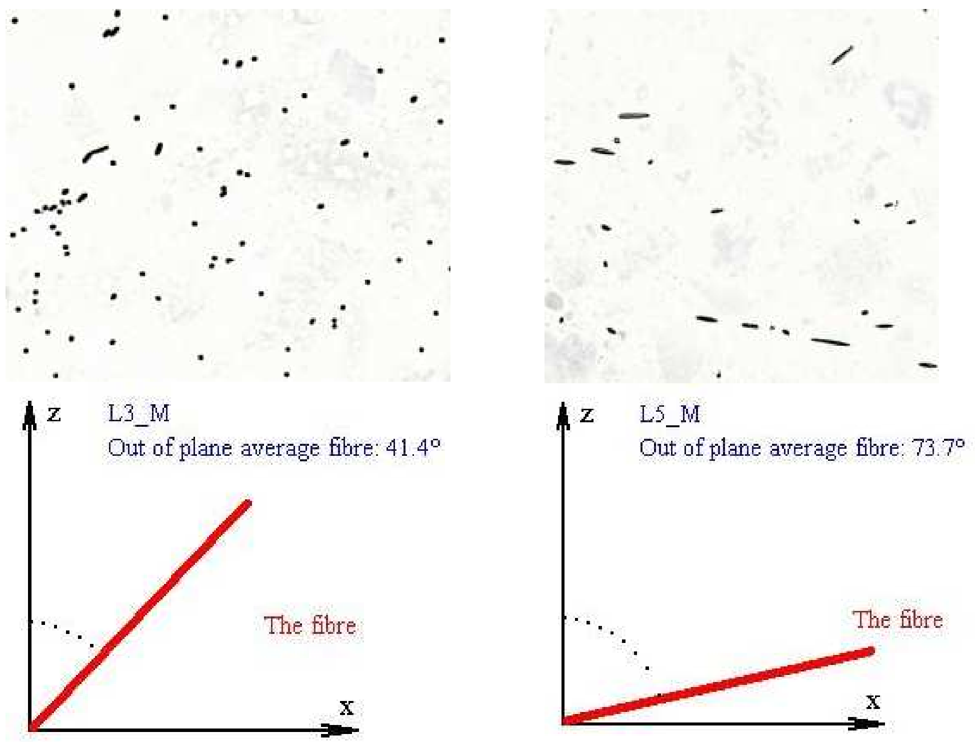


If two types of fibres are present two colour markers can be used. Afterwards the laminate is torn off the concrete sample and glued to white sheet of paper (Cf.Fig.3). The image acquisition in this case can be performed by scanning the sheet in a flatbed scanner.

Figure 9. Fibre marking process and scanned image of markings.

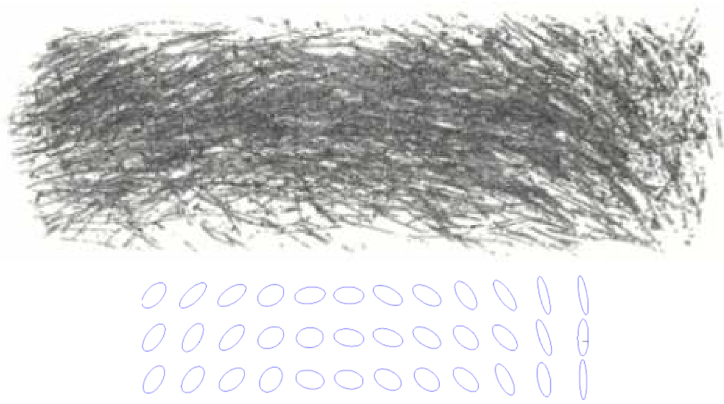
During this procedure the information about fibre orientation out of plane is lost, but still it’s possible to count the amount and distribution of fibres. The sharp difference between black dots and white background makes it easier for the program to analyse the picture with less error on determining the fibre amount. Based on this literature review the plugin for the open source image analysis program FIJI was developed. The plugin can analyse both direct image of FRC cut surfaces and manually marked fibre scanned images. Furthermore it calculates the fibre out of plane average angle (Cf.*Figure 10*).

Figure 10. Images of FRC samples and their average out of plane angles



Computerised X-ray tomography (Computed tomography) is a radiological imaging technique first developed in Great Britain by Hounsfield in 1972. It revolutionised medical radiology by producing anatomical images of high accuracy [14]. By comparison to fixed X-ray imaging, CT scanner projections are typically collected at fixed angular increments while the sample is either rotated continuously or step scanned. In clinical X-ray tomography systems the sample is held fixed while X-ray source and detectors are rotated [15]. In any case projections obtained in many different angles are processed in a computer using reconstruction algorithms. As a result 3D CT images can be reconstructed from cross sectional slices. For CT scan visualisation, the economically most relevant method is to use open source programs (such as Fiji, ImageJ, 3D slicer) capable of visualising CT scan data into 3D pictures. But still it is quite difficult to evaluate CT scan pictures visually just from reconstructed 3D images. The fibres can be seen as a mesh of wires (Cf.*Figure 11*a) where the orientation pattern is difficult to distinguish. One of the possible methods for visualisation of the fibres is to use ellipsoids to show the orientation tendency in the zone of interest of the FRC sample. To obtain ellipsoids image first the threshold with FIJI is applied software to separate fibres from rest of the image. Then the FIJI skeletonise plug-in is used to find centre lines of fibres [16]. After centre lines are found "Analyse skeleton" plugin is applied. When executing the analysis as a result summary window "Branch information" is displayed. The summary table is saved as .xls file. Then a special Matlab developed by authors is run. It automatically reads values from the xls file and produces image of ellipsoids (Cf.Fig.5b).

Figure 11. 3D image of FRC beam CT (a) and simplified ellipsoids (b) view.



DISCUSSIONS

To determine the fibre number crossing a FRC sample surface the most reliable method is manual fibre counting. This technique is applicable presupposed that the fibre diameter is big enough to be visually detectible.

To improve the efficiency the labour some manual counting method can be replaced by image analysis. On the other hand to acquire a good quality image (the way fibres in the image would not look similar as sand particles or pores) is a challenging process. In this case hand marked fibres on a transparent film technique is quite useful, e.g. two or more fibre types can be marked in different colours. If samples are steel fibre reinforced, a cut surface can be polished in order to obtain fibre out of plain angle using image analysis software. This gives knowledge of how effective fibres are orientated towards a desired direction. However the superior solution for 3D fibre orientation analysis is Computerised Tomography as described above. All mentioned methods are widely used in research projects but they can be applied in an industrial quality control as well. For this purpose drilled or cut samples from certain FRC structural elements must be taken. As research shows [9] counting of fibre number crossing the drilled core surface for plotting rose graphs doesn't provide sufficiently clear results on fibre orientation, and consequently drilled cores should be grinded to a cubical shape. While direct methods can be used for analysis of FRC samples which also have some ordinary reinforcement, indirect methods described in literature so far are tested on only fibre reinforced samples.

CONCLUSIONS

For small amount of specimens manual counting of fibres should be used to determine the fibre distribution and orientation. If obtaining a good quality image of FRC surface for digital image analysis is a problem, a technique with hand marking on transparent film should be used. Average out of plane orientation angle obtained from image analysis can be used for determining fibre orientation towards direction perpendicular to cut surface when CT scanning equipment is not available. The CT method is so far the best method and gives good understanding on fibre orientation in the FRC specimen when using view simplification.

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