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# Structural elements made with highly flowable UHPFRC: Correlating computational fluid dynamics (CFD) predictions and non-destructive survey of fiber dispersion with failure modes

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ABSTRACT

Structural design with highly flowable Fibre Reinforced Concrete has to duly take into account the preferential alignment of fibers, which can be governed through the rheological properties of the fluid mixture and the casting process and by the geometry of the structure. The possibility of predicting the fiber alignment, by tailoring the casting process, and of non-destructively monitoring it, can foster more efficient structural applications and design approaches.

Focusing on UHPFRC slabs with pre-arranged casting defects, the flow-induced alignment of the fibers has been predicted by means of a suitable CFD modelling approach and hence monitored via a non-destructive method based on magnetic inductance properties of the fiber reinforced composite. The comparison between the assessed data on the fiber orientation and the crack patterns as visualized by image analysis supports the effectiveness of casting flow modelling and non-destructive fiber dispersion monitoring in supporting the structural design of elements made with highly flowable fiber reinforced cementitious composites.



## 1. Introduction

The advent of Ultra High Performance Fiber Reinforced Concrete and Cementitious Composites (UHPFRC, UHPFRCCs) on the construction market, a few decades ago, has paved the way for a novel approach to the concept and design of civil engineering structures and infrastructures.

On the one hand, the high deformation tolerance and energy dissipation capacity allows optimizing the dimensions of "conventional" structural elements (beam- and column-like) thanks to a more efficient structural use of the material. As a consequence, longer spans could be covered and higher load bearing capacity (or even larger lateral load resistance in the case of earthquake-resistant structures) could be achieved with reduced section dimensions, thus also reducing the self-supporting structural burden [1–3]. The enhanced performances in the hardened state are often associated with a superior performance in the fresh state. From the architectural point of view hence structural functions and complex shapes, which are hard to be cast with conventional reinforced concrete, can be easily obtained with UHPFRC [4–7].

In this framework, the dispersion of fibers inside a structural element, which is well recognized as a crucial issue in the reliability of structures made of Fiber Reinforced Concrete and Cementitious Composites plays a twofold role [8,9].

First of all a non-uniform dispersion of fibers, with zones with a reduced amount of fibers, may seriously affect the load bearing capacity as well as trigger unexpected failure mechanisms. Previous researches have pointed out that the non-uniform dispersion of fibers most likely occurs due to the negative effects of high fiber contents on the rheological properties of the fresh mixture [10,11]. A successful casting of conventional Fibre Reinforced Concrete (FRC) usually requires compaction and/or vibration, which may cause sedimentation of fibers, whereas contributing to an uneven

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spatial distribution of material mechanical properties inside the element.

Secondly, thanks to the synergistic effect with the superior fresh-state performance of UHPFRC, the need for manual compaction and vibration is reduced, resulting into a randomly uniform dispersion of fibers as well as into a more uniform spatial distribution of the material properties in the hardened state [12]. It has been furthermore shown that, thanks to both a suitably balanced set of fresh state properties and to a careful design of the casting process, it is possible to effectively orientate the fibers along the direction of the casting flow [13–15]. Both controlling and monitoring the fiber orientation during the casting process, is the first fundamental step towards a promising "holistic" approach to tailor the structural performance of UHPFRC structural elements. That is, enforcing the orientation of fibers along the direction of the principal tensile stress within the structural element when in service, will allow a more efficient structural use of the material to be effectively pursued [16–40]. Preferential orientation of fibers also jeopardize the isotropic material behavior assumption; the resulting even strongly orthotropic mechanical behavior of the material has to be duly taken into account in structural design, most of all when dealing with slab and shell structures which experience complex biaxial stress field arising from different load combinations.

The aforementioned "holistic design approach" for structures made with highly flowable FRC relies on two main "pillars" [41,42]. First, a reliable tool is needed, which predicts the alignment of the fibers by considering the rheological material properties and the casting process, including the geometry and boundary conditions of the structure to be cast; then, the assessment of the fiber distribution through a non-destructive time- and cost-effective method becomes a crucial quality control procedure.

## 2. Non-destructive monitoring of fiber dispersion

The early works on non-destructive monitoring of fiber dispersion in FRC structural elements employed X-ray imaging [43]. Besides the safety concerns related to the use of X-ray equipment on industrial scale, it is worth remarking that such methods, which have been also widely used thereafter by several researchers, mainly as a pre-check of destructive analyses [11] are able to provide an immediate visualization of the discrete fiber reinforcement network inside the analyzed region of the element, mainly in the case of steel fibers. As a matter of fact, the thickness of the element, in order to have meaningful information from the images, has to be necessarily limited, as a function of the power of the employed equipment and of the X-ray absorption capacity of the material. Furthermore, the unavoidable "loss" of the third dimension may introduce some artifacts in the results of image processing, affecting any quantitative information, e.g. about local fiber density, which could be garnered from it. The higher the fiber dosage and the aspect ratio of the fiber, the more influence have these artifacts.

Electrical methods, based on the effects of the fibers on the resistivity/conductivity of the composite material, have received lots of attention up to very recent years [44,45]. Ozyurt et al. [46] employed the Alternate Current Impedance Spectroscopy (AC-IS) for the detection of fiber dispersion related issues and demonstrated its reliability as well as its sensitivity to fiber orientation, clumping, segregation, etc. by means of extensive comparison with results obtained from destructive methods. Attempts were also made to address the application of the aforementioned method to industrial scale problems [47]. The method consists of applying to the specimen a voltage excitation over a wide range of frequencies (e.g. 10 MHz–1 Hz) and measuring the amplitude and phase of the flowing current. When considering direct current (DC) or low frequency alternate current (AC), the behavior is practically insulating. However, the impedance Z significantly drops under high frequency alternate current excitation as a result of the displacement current. When the real and imaginary parts of the calculated impedance are plotted on a Nyquist diagram, FRCCs exhibit the so called dual-arc behavior, with two cusps, each of them represents a local minimum of the imaginary part of the impedance with respect to the real part. The rightmost cusp corresponds to the DC resistance across the electrodes, whose real part of the impedance $R_m$ is essentially due to the matrix. Previous works have shown that it is weakly affected by the presence of the fibers. The leftmost, high frequency cusp is strictly related to the presence of conductive fibers in the matrix. It can be shown that the real part of the impedance R depends on the conductivity of the composite material. $R_m$ and R can thus be used to estimate the concentration of the fibers by means of a simple mixture rule. In order to overcome the drawback of the sensitivity to moisture conditions, the so-called normalized resistivity is used:

$$\frac{R_m}{R} = 1 + [\sigma_{fibers}]V_f \tag{1}$$

where $V_f$ is the fiber volume fraction and $\sigma_{fibers}$ is the intrinsic conductivity of the fibers which, in the case of highly conductive fibers, only depends on their aspect ratio, which may affect the possibility to apply the method to the case of hybrid fiber reinforcement.

The method has been extensively employed to assess the influence of the fresh state performance on the dispersion and orientation of the fibers [12], clearly highlighting the better uniformity in fiber dispersion achievable through FR-SCC, together with a sensitivity to flow induced fiber alignment. Any direct quantitative comparison between, e.g., the concentration of fibers, as evaluated from Eq. (1) and data obtainable from destructive tests (e.g. crushing samples, separating and weighing fibers) could hardly be found in the literature. The need of a dedicated expensive instrumentation, required by the width of the employed frequency range, and the sensitivity of the method to the contact impedance between the surface electrodes and the structure surface, stand, so far, as the main hindrance to a wide application of the method at the industrial scale.

In order to overcome this problem, a method has been developed based on the evaluation of the equivalent capacitance between the electrodes of a probe which has to be simply laid on the surface of the structure under test. The technique allows assessing information about the average fiber concentration and their average direction. The measurement frequencies are relatively low (unto few hundreds of kilohertz) so that the required instrumentation is easily available and relatively inexpensive. However, the method suffers from high sensitivity to the humidity and to the coupling between the electrodes and the specimen.

Lataste et al. [48] employed a method based on low frequency resistance measurements, with a four electrode arrangement, aimed at reducing the effects of the poor electrical coupling. The method has been demonstrated to be effective in detecting orientation characteristics of the dispersed fiber reinforcement, because of the different resistance measured along the two directions at right angle to each other; a qualitative correlation with mechanical properties measured along the same directions as above was also provided [49,50]. The method is by the way not able to provide any quantitative information about the local average concentration of the fibers. This is mainly due to the strong sensitivity of the concrete matrix resistivity to aging, moisture content and presence of electrolytes in the pores, which also affect the measured resistivity, beside the effect of fiber concentration.

The effects of conductive fibers on the dielectric properties of the fiber reinforced composite have led to the development of another method, based on the measurement of the effective