Tailoring the orientation of fibres in high performance fibre reinforced cementitious composites: part 1 – experimental evidence, monitoring and prediction

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1 Introduction

The idea of embedding fibres into a 'stone-like' matrix to temper its brittleness can be traced back to the inclusion of straw fibres into sun-dried bricks (adobe), already documented in ancient Mediterranean civilisations (Clarke and Engleback, 1990). Focusing the attention on fibre reinforced concrete (FRC) it dates back to the early sixties, when the early systematic research work started being published (Romualdi and Batson, 1963; Romualdi and Mandel, 1964). Henceforth, a field of fruitful research and engineering applications has originated: the chapter dedicated to the design of FRC structures in the new Model Code 2010 stands as the latest milestone achievement in this field.

Elaborating the concepts developed by the aforementioned authors, and already inborn in the idea of 'ferrocement' put forward by Nervi (1956) in the '40s (see also Shah and Naaman, 1978), FRC can be regarded as a sort of 'scale refinement' of the basic idea underlying conventional reinforced concrete. Because of their smaller size and of their random distribution "through the volume of concrete at much closer spacing than can be obtained by the smallest reinforcing rods" (Batson et al., 1972), fibres can arrest crack propagation for smaller crack openings, and hence at an earlier stage. This will contribute to enhance to toughness of the material, i.e., exactly its resistance to crack propagation. This concept has been further developed in the last couple of decades into to the so called 'ladder-scale' fibre reinforcement, where, e.g., blends of fibres with different dimensions, from millimetres to micrometres to even nanometres, are added to a concrete matrix. Owing to their different sizes, different fibres can interact with the cracking process at different stages of its propagation. This provides greater and greater enhancement not only to toughness but also to strength and elastic properties, because of delaying crack coalescence, reducing widening of coalesced cracks and inducing multiple cracks before the peak load (Lawler et al., 2003). Cementitious composites reinforced with carbon nanotubes (Konsta Gdoutos et al., 2010) represent the latest development, through which it can be envisaged the possibility of engineering manipulating material properties at the nano-scale, aiming to achieve a defect free material (Gao et al., 2003).

The concepts of 'multi-scale' design of a material have been successfully pursued in the wide area of fibre reinforced cementititious composites (FRCCs). Micromechanics-based design represents the current state of the art for high performance fibre reinforced cementitious composites (HPFRCCs), with specific reference to their special category of engineered cementitious composites (ECCs). The fracture mechanics concept of arresting the propagation of cracks into the brittle matrix thanks to the bridging effect provided by the fibres bonded to the matrix itself is worked out to obtain stable multiple cracking and tensile strain hardening behaviour before the onset of the unstable macro-crack localisation.

Fracture mechanics has provided analysis tools, which encompass the micromechanics of crack bridging mechanisms provided by the fibres and the 'macroscopic' concepts of fracture toughness and characteristic length of the fracture process. These concepts have allowed each FRCC to be regarded as a macroscopically homogeneous material. The 'tensile constitutive relationship' to be employed for design to be identified in a framework consistent with design approaches currently employed also for reinforced concrete structures (*Fib* Model Code for Concrete Structures, 2010). In this framework, fracture mechanics can also provide a unifying approach for both strain-hardening and strain-softening FRCCs, by associating different characteristic lengths to either stable multiple crack propagation or unstable crack localisation processes. This unifying approach is highly needed. As a matter of fact, the same material, because of different alignment of fibres to the applied tensile stress, can exhibit either one or the other behaviour, whether stressed parallel or orthogonally to the main preferential fibre alignment (Ferrara et al., 2011, 2012e).

Along the 50 year odyssey of FRCCs (Di Prisco and Ferrara, 2011), the issues related to fibre dispersion have proved themselves of the utmost importance to achieve the desired effects on the engineering properties of the composite. The dispersion of the fibres was also recognised as a crucial for the effective development of the toughening action exerted by the fibres (Batson et al., 1972). Nevertheless, it was also quite earlier recognised that the not seldom hypothesised randomly uniform dispersion of the fibres within a cast element could hardly be achieved, because of the negative effects that fibres themselves have on the workability of fresh concrete (Bayasi and Soroushian, 1992). Because of this, casting of elements made with FRCs hardly could be accomplished without external interventions, such as manual compacting and vibration. These, on their hand, could jeopardise the above recalled random uniformity of fibre dispersion. It is worth here remarking that a poor dispersion of fibres in a structure, affected by casting and processing, is not only a mere technological problem. In fact spots with a reduced fibre dosage or no fibres at all act as flaws and trigger early failures by activating unpredictable mechanisms, that affect the load-bearing capacity and the structural performance as a whole, e.g., in terms of bending stiffness, fracture toughness, ductility, etc.

The advances in the technology of self compacting concrete (SCC), in the last decade, have led to the development of admixtures and innovative concept about granular packing and mix design criteria which have been instrumental to successfully solve the aforementioned issues for workability and fresh state performance of FRCC. This has furthermore made possible the successful design and casting of fibre reinforced self-compacting concretes (FRSCCs – see Ferrara et al., 2007b). The major advantage of incorporating fibres into self-compacting concrete is the achievement, thanks to the elimination of compaction and vibration and to the rheological stability of the SCC matrix, of a randomly uniform dispersion of fibres within structural elements, not even affected by their segregation (Ferrara and Meda, 2006; Ozyurt et al., 2007; Ferrara et al., 2008). This requisite is, as mentioned above, of paramount importance for a reliable structural performance of elements made with fibre reinforced cementitious composites. It has also been recently recognised that, through a suitably balanced performance of the fluid mixture, fibres can be effectively aligned along the casting-flow direction (Ozyurt et al., 2006a; Stahli et al., 2008; Barnett et al., 2010; Boulekbache et al., 2010, 2012; Torrijos et al., 2010; Ferrara et al., 2011, 2012e; Kang and Kim, 2011). By suitably tailoring the casting process to the intended application, the flow direction of the fresh concrete, along which fibres tend to be aligned, can be made to coincide, as closely as possible, with the anticipated stress pattern (i.e., the direction of principal tensile stresses) within the structural element when in service. This would lead to a better structural efficiency of the material which can also result into optimised structure size and reduced self weights. Results in cited references provide solid experimental evidence to the aforementioned statements. Furthermore, a rheology/fluid mechanics-based approach to the fresh state performance related issues, and to the casting process of fresh concrete have allowed the fundamentals to be highlighted of the mechanics of flow induced fibre orientation.

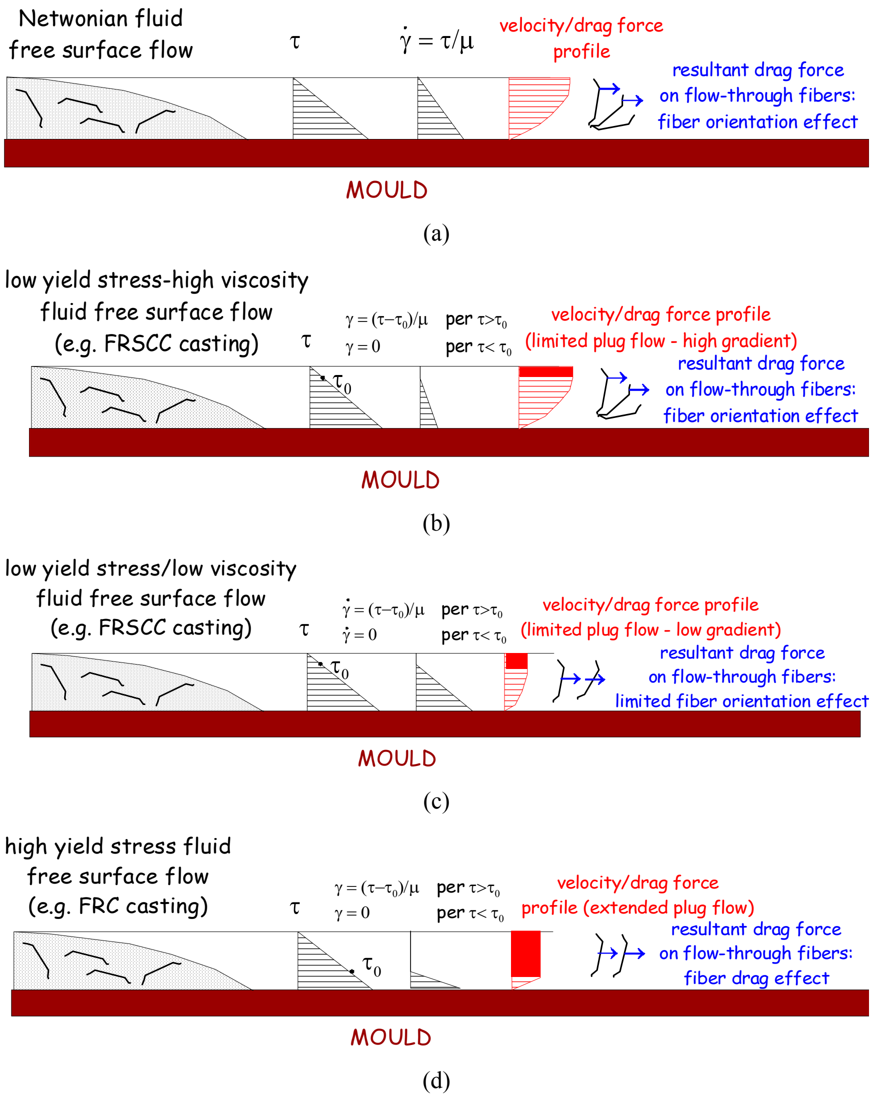
Clearly the performance of the structure is the outcome of the synergy between fresh and hardened state properties of the material and fibre dispersion and orientation related issues, as obtained through casting and processing and as a function of the structure geometry. Understanding the correlation among these factors allows to govern them and to design the material for the performance required by the intended structural application. Furthermore the casting process can be tailored to the application in order to obtain, e.g., the most suitable, alignment of fibres, which is its most close correspondence with the direction of principal tensile stresses within the element when in service. This requires, on one hand, suitable modelling and prediction tools for both the fresh state behaviour and the casting flow but also for the prediction of the orientation of the fibres, which has to be usefully employed in industrial practice. On the other hand, suitable methods and sensors are likewise highly needed to monitor the dispersion and orientation of the fibres as achieved in the structure because of the tailored casting process. In a design oriented perspective, a flow-induced fibre orientation obviously affects not only the experimental procedure for the identification of the material design parameters, including the concept of specimen geometry and manufacturing. Moreover, it affects the design concept as a whole, which has to consider the flow induced anisotropy of the material and its structural outcomes. On the other hand it has to be remarked that, right because of the synergistic effects between fresh state performance, fibre dispersion/orientation and mechanical hardened state performance of the material in the structure, a 'holistic' design approach can be conceived, which tailors both the material composition and the casting process to the anticipated structural performance. This would require the orientation of fibres to match as close as possible with the direction of the principal tensile stress within the structural element when in service, so to achieve a more efficient structural use of the material. In this way a desirable closer correspondence between the shape of an element and the function it performs in a structure assembly could be pursued in the design. A suitably balanced fresh-state performance of the fibre reinforced cementitious composite would allow to mould the shape of an element and, thanks to a tailored casting process, to align the fibres along the direction of the principal tensile stresses resulting from its structural function.

This paper, with its companion Part 2, will review, in the framework of the international state of art, the major research achievements by the author in the aforementioned field. In Part 1, a review will be first performed with reference to experimental evidence of a flow induced orientation of fibres in highly flowable FRCCs. The mechanisms of orientation of fibres in a yield stress fluid flow will be then discussed and the most recent developments will be addressed in the field of modelling and prediction of this phenomenon, as well as with reference to the non-destructive monitoring of fibre dispersion and orientation related issues. Part 2 of the paper will hence focus on the effects of flow induced orientation of fibres on the mechanical properties of the composite and will highlight its outcomes in terms of structural design of engineering applications.

2 Alignment of fibres in a casting flow: experiments and physical mechanisms

Over the past ten years, several dedicated experimental investigations, performed at the scale of both lab specimens and full size mock ups and applications, including, among the others, precast beams and tunnel segments (Grunewald, 2004; Ferrara and Meda, 2006) have clearly demonstrated the feasibility of achieving a tailored alignment of fibres along the direction of the casting flow in elements made with highly flowable or self-compacting FRCs.

Figure 1 Mechanisms of flow-induced orientation of fibres in a free surface flow of Newtonian fluid (a), yield stress fluid with low yield stress and with high or low viscosity (b–c), high yield stress fluid (d) (see online version for colours)



The preferred orientation of the fibres is due to two main concurrent phenomena. (Martinie, 2010; Martinie and Roussel, 2011). Flows dominated by shear stresses, to which category many real casting cases belong, feature a parabolic flow-velocity cross profiles and a likewise distribution of drag forces. These, acting transverse to the axis of a fibre immersed in the flow, is likely to induce a torque which makes the fibre itself to align parallel to the flow direction, along which this torque becomes minimum [Figure 1(a)]. In the case of a yield stress fluid, the cross profile of flow-velocity, is characterised by a plug-flow zone. This is defines as a zone across which, being the shear stress lower than the yield strength, the flow features a constant velocity profile. Null or negligible value torque results hence on the fibre and no preferred alignment can be obtained [Figure 1(b)]. The through-flow extension of the plug-flow zone depends on the value of the yield stress, the higher the latter the thicker the former [Figures 1(b)–1(d)]. The viscosity of the fluid, on its hand, governs the gradient of the flow velocity profile and hence of the drag forces acting transverse to the fibre axis and the magnitude of the resulting 'fibre-orientating torque' [Figures 1(c)–1(d)]. It has been furthermore shown (Martinie and Roussel, 2011) that this alignment can be practically considered, at the scale of industrial casting processes, as an almost instantaneous phenomenon. It in fact occurs in a 'maximum fibre orientation characteristic time' which is of the order of a couple seconds, which is far shorter than the duration of any real casting process.

The second cause for preferred alignment of fibres is the so called 'wall effect': as a matter of fact "it is indeed not possible to find a fibre perpendicular to a wall at a distance lower than half the length of the fibre" (Martinie and Roussel, 2011).

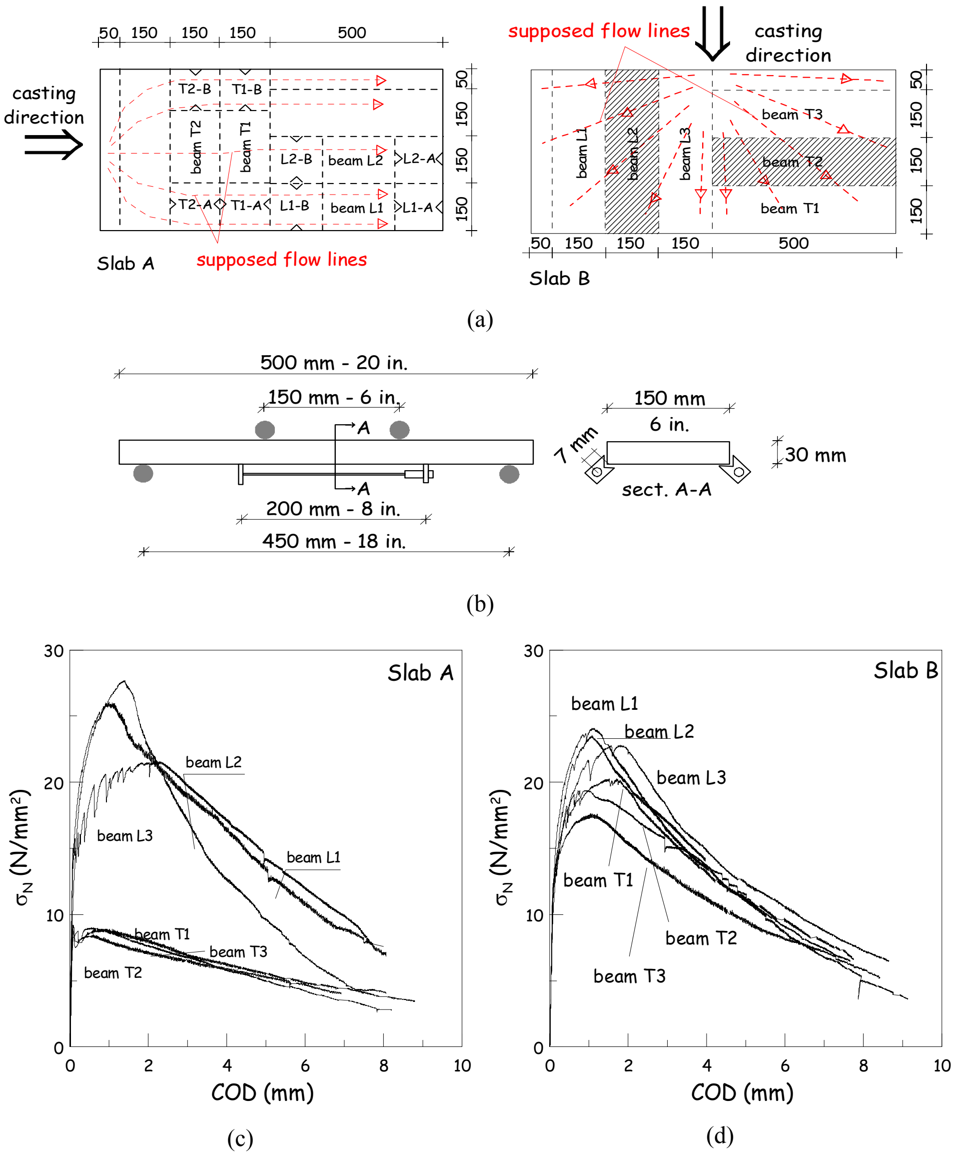
Grunewald (2004) tested SFR-SCC beams, in which flow casting was parallel to the beam axis which induced a most likely alignment of fibres parallel to the direction of the applied bending stress. He reported superior toughness than in beams which were manually cast with a vibrated SFRC having the same strength class and the same fibre content, also irrespective of the similar measured fibre pull out strength. Wille and Parra Montesinos (2012) confirmed the same influence of the casting process on the flexural toughness of highly flowable FRCS.

Table 1 Mix design and fresh state performance of the HPFRCCs employed in investigation detailed in Ferrara et al. (2011, 2012d, 2012e)

Mix design (dosages in kg/m^3)			
Constituent	*HPFRCC 100*	*HPFRCC 50*	*HPFRCC 0*
Cement type I 52.5	600	600	600
Slag	500	500	500
Water	200	200	200
Superplasticiser	33 (l/m^3)	33 (l/m^3)	33 (l/m^3)
Sand 0–2 mm	983	1,000	1,017
Steel fibres (13/0.16)	100	50	0

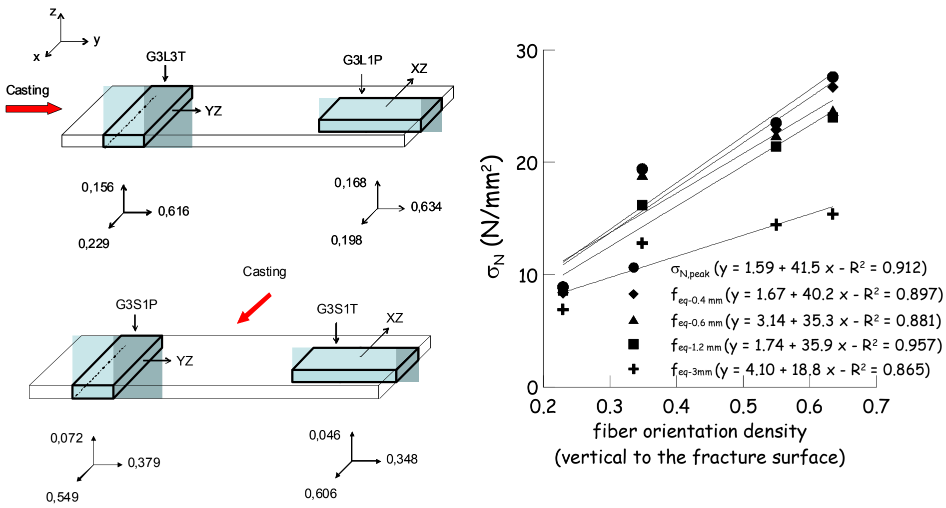
Ferrara et al. (2011) performed a comprehensive investigation on thin slabs made with a self-levelling/highly flowable HPFFRCC (mix design labelled as HPFRCC100 in Table 1). The slab specimens were casted, as shown in Figure 2(a), in such a way that different flow induced fibre orientation patterns were obtained. 150 mm wide and 500 mm long beams were then cut from the slabs, with their axis, i.e., the direction of the bending stress to be applied during 'toughness' testing, at different angles to the visually inspected direction of the casting flow, i.e., the most likely 'flow induced' preferential alignment of the fibres [Figure 2(b)]. The mechanical performance of the material, measured by means of four-point bending tests performed on the beams according to the scheme shown in Figure 2(c). A careful identification of the orientation of fibres on the specimen fracture surface, performed through image analysis, provided solid confirmation to an educated guess about the flow induced alignment of the fibres and its outcomes on the mechanical properties of the material [Figures 2(d)–2(f)]. Similar results were obtained by several other authors (Stahli et al., 2008; Barnett et al., 2010; Boulekbache et al., 2010; Torrijos et al., 2010; Kang and Kim, 2011; Ferrara et al., 2012e) with reference to both the tensile and bending behaviour of highly flowable FRCCs.

Figure 2 Influence of flow induced fibre orientation on HPFRCC toughness, (a) casting scheme (b) 4pb test set-up (c–d) nominal stress-cod curves (e) fibre orientation densities (f) post-cracking equivalent strengths vs. orientation density (see online version for colours)



Source: Ferrara et al. (2011)

Figure 2 Influence of flow induced fibre orientation on HPFRCC toughness, (a) casting scheme (b) 4pb test set-up (c–d) nominal stress-cod curves (e) fibre orientation densities (f) post-cracking equivalent strengths vs. orientation density (continued) (see online version for colours)



(e) (f)

Source: Ferrara et al. (2011)

3 Fibre dispersion monitoring

In most of the studies cited in the previous sections, the orientation of the fibres was checked by manual counting and only with reference to selected 'specimen locations', such as on the fracture cross-sections of specimens after toughness tests. Manual counting is rather easy when low dosages of longer fibres with average aspect ratios are employed (Ferrara et al., 2007a; Vandewalle et al., 2008). Image analysis techniques are required for higher dosages of shorter fibres with higher aspect ratios or whenever a quantitative information on the orientation of fibres with respect to the plane of the cut has to be sought (Grunewald, 2004; Torrijos et al., 2010; Sanal and Ozyurt, 2010; Ferrara et al., 2011).

The development of a time- and cost-effective non-destructive method for the assessment of fibre dispersion and orientation in FRC structural elements has hence become a crucial need. Furthermore, it is desirable that this method could be implemented into an 'ad-hoc' quality control procedure, instrumental to anticipate undesired scattering of mechanical properties due to poor fibre dispersion (Ferrara et al., 2012b).

X-ray pictures of cores or of thin slices obtained by sawing the specimens (the sample thickness is dictated by the absorption properties of the material and power of the X-ray equipment) were taken in several investigations (Stroeven and Shah, 1978; Ferrara and Meda, 2006; Vandewalle et al., 2008). They provided immediate and effective visualisation of the fibre orientation, but hardly any quantitative information could be obtained from them, both due to the loss of the third dimension and in the case of higher dosages of short fibres.

Electrical methods, based on the effects of the fibres on the resistivity/conductivity of the composite material, has received lots of attention in the very last years. Ozyurt et al. (2006b) employed the alternate current impedance spectroscopy (AC-IS) for the detection of fibre dispersion related issues. They demonstrated the reliability of the method as well as its sensitivity to fibre 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 (Ozyurt et al., 2006a). The method is based on the frequency-dependent behaviour of cementitious composites reinforced with conductive fibres, such as steel and carbon ones. These were in fact shown to be practically insulating under direct current (DC) and low frequencies alternate current (AC) while they are conductive under high frequencies AC. 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 the real and imaginary parts of the calculated impedance Z are plotted on a Nyquist diagram, FRCCs exhibit the so called dual-arc behaviour [Figure 3(a)]. It features a low-frequency cusp (fibres act insulating), which gives the (higher) resistance of the matrix, R_m, and a high frequency cusp (fibres are conductive), which corresponds to the (lower) resistance of the fibre reinforced composite R. In order to overcome the drawback of the sensitivity to moisture conditions, the so-called matrix normalised conductivity is used, from which in-formation about local fibre concentration should be easily obtained by means of a simple mixture rule approach:

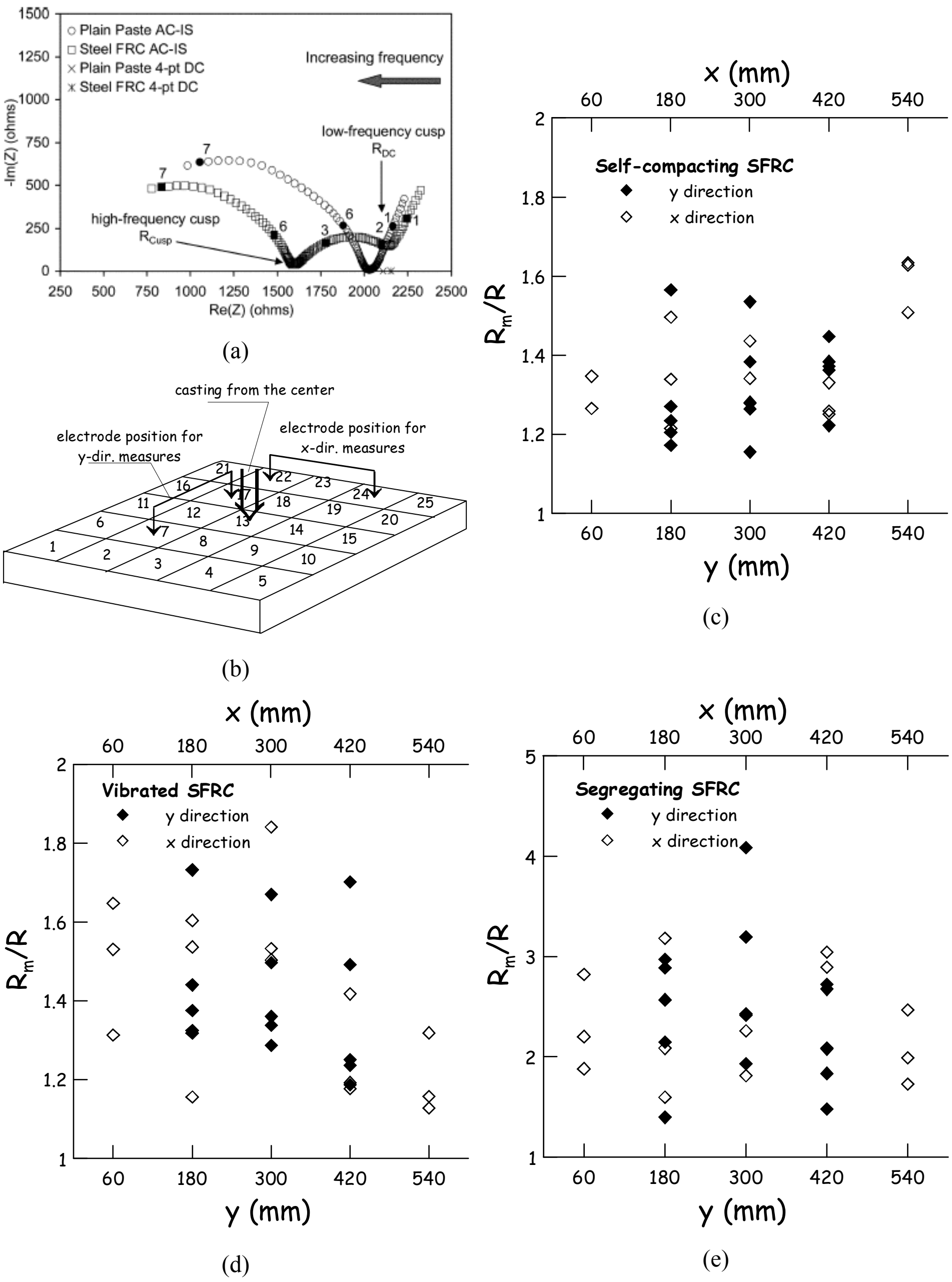
$$\frac{R_m}{R} = \frac{\sigma}{\sigma_m} = 1 + \left[\sigma_{\text{fibers}}\right] V_f \tag{1}$$

where σ and σ_m are the conductivities of the fibre reinforced composite and of the matrix respectively, $[\sigma_{\text{fibres}}]$ is the intrinsic conductivity of the fibres which, in the case of highly conductive fibres, only depends on their aspect ratio, and V_f is the fibre volume fraction.

Table 2 Mix design of FRCs employed in investigation detailed in Ferrara et al. (2008)

	SFRC	*SFR-SCC*	*Segr. SFRC*
Cement type I – kg/m^3	355	400	440
Fly ash type C – kg/m^3	132	148	164
Water – kg/m^3	166	186	205
Water / binder	*0.34*	*0.34*	*0.34*
Polycarboxilate superplasticiser – lt/m^3	24	27	30
SP dosage (by % of binder)	*0.45*	*0.45*	*0.45*
Sand 0–4 mm – kg/m^3	975	918	861
Gravel 4–9.5 mm – kg/m^3	795	749	703
Steel fibres 65/35 – kg/m^3		50	

Figure 3 Principle of AC-IS method for fibre dispersion monitoring and correlation between fresh state performance and fibre dispersion in slabs cast with fibre reinforced cementitious composites with different rheology: (a) example of a nyquist plot for plain and fibre reinforced cement pastes, (b) scheme for AC-IS measurements on 600 mm square slabs and (c) matrix normalised conductivities for FR-SCC, (d) vibrated and (e) segregation prone SFRC plates



Source: Ferrara et al. (2008)

The method has been extensively employed to assess the influence of the fresh state performance on the dispersion of the fibres (Ferrara et al., 2008; mix designs employed in this investigation are listed in Table 2), clearly highlighting the better uniformity in fibre dispersion achievable through self compacting concrete (Figure 3). By the way, any direct quantitative comparison between, e.g., the concentration of fibres, as evaluated from equation (1) and data obtainable from destructive tests (e.g., crushing samples, separating and weighing fibres) could hardly be found in the literature. The need for 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.

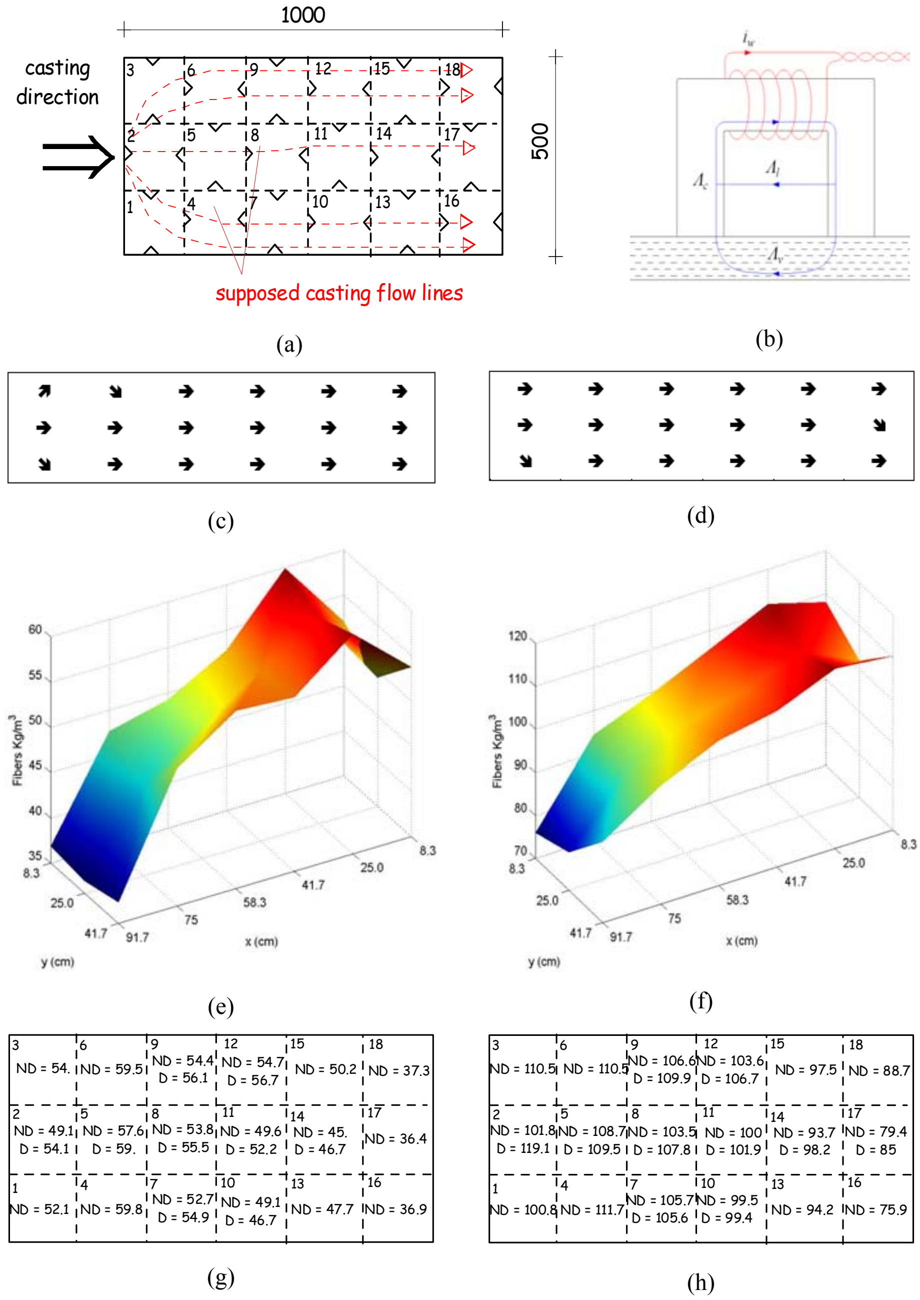
Lataste et al. (2008) employed a method based on low frequency resistance measurements, with a four electrode arrangement, aimed at reducing the effects of the poor electrical coupling. The method has been demonstrated to be effective in detecting orientation characteristics of the dispersed fibre reinforcement, because of the different resistance measured along the two directions at right angles to each other. Qualitative correlation with mechanical properties measured along to the same directions as above was also provided (Barnett et al., 2010). Anyway the method is not able to provide any quantitative information about the local average concentration of the fibres. This is mainly due to the strong sensitivity of the concrete matrix resistivity to ageing, moisture content and presence of electrolytes in the pores which also affect the measured resistivity, beside the effects of fibre concentration.

The effects of conductive fibres on the capacitive properties of the fibre reinforced composites have led to the development of another method, based on the measurement of the effective permittivity through a coaxial probe and microwave reflectometry techniques (Van Damme et al., 2004). The local average concentration of fibres could be assessed by assuming a random orientation and because of the known fibre geometry (aspect ratio) which governs their capacitive behaviour, but the method is not sensitive to a preferential alignment.

Methods based on the study of heat transients and on the effect of fibres on the thermal diffusivity of the composite have been also tentatively applied for the non-destructive assessment of fibre concentration (Felicetti and Ferrara, 2008). Temperature fields within a structural element may be easily surveyed through IR thermography, but the slow propagation of temperature variations in thick members, which makes it difficult to provide a controlled input excitation over large areas, may limit the applicability of the method.

Computed axial tomography (CAT) scanning allows effective 3D visualisation of the fibre network inside a FRC specimen (Stahli et al., 2008; Molins Borrel et al., 2008). Limits on specimen size together with the need of a dedicated equipment and of an image analysis software for the quantitative processing of the collected data stand so far as the main concerns in promoting the method for wider use, especially at the industrial scale.

Figure 4 (a) Scheme of slab casting for fibre orientation testing and calibration of magnetic method for ND monitoring of fibre dispersion, (b) scheme of the measuring set-up, directions of maximum magnetic inductance for HPFRCC with (c) 50 and (d) 100 kg/m^3 fibres; estimated fibre content for (e) 50 and(f) 100 kg/m^3 fibres and comparison between ND inferred and destructively measured content for (g) 50 and (h) 100 kg/m^3 fibres respectively) (see online version for colours)



Source: Ferrara et al. (2012d)

A method that which employs a probe sensitive to the magnetic properties of the steel fibres has been recently proposed and validated (Faifer et al., 2011; Torrents et al., 2012). The fundamentals of the method rely on the fact that the presence and relative position of the fibres in a FRC element modify the magnetic circuit of the employed probe, when placed on the element/structure surface. This results in a variation of the measured inductance. Both fibre concentrations can be quantitatively assessed by suitable calibrating the method and fibre preferential orientation can be estimated. The method, besides its good sensitivity and robustness, is also characterised by an intriguing ease of use. As a matter of fact it features simple equipment which just needs to be positioned on the surface of a structural element, which can be easily done even on vertical elements or slabs accessible only from the bottom, without any dedicated care about the electrical coupling. The method has been applied in a recent study (Ferrara et al., 2012d, 2012e) to quantitatively demonstrate the ability of a self consolidating mortar matrix to disperse and orientate steel fibres along the flow direction in a slab-casting case study (mix-designs employed for this investigation are summarised in Table 1). Extensive calibration was also performed by means of comparison with destructive evaluation of both fibre orientation, through image analysis of slab cross sections at selected locations, and fibre dispersion, evaluated by specimen crushing and fibre separation with a magnet (Figure 4).

4 Numerical prediction of flow-driven fibre orientation

With the aim of tailoring the casting process to the anticipated performance of the intended application, the prediction of fibre orientation as a function of the fresh concrete properties, casting flow geometry and casting process plays the major role. The alignment of fibres with the direction of the principal tensile stresses within the element when in service has to be sought. Numerical modelling of fresh concrete flow has been recently recognised as an effective tool to simulate casting processes and optimise them with reference to specific applications (Roussel et al., 2007a). Computational fluid dynamic (CFD) approaches, based on the Galerkin FEM formulation of the Navier Stokes equations and including moving boundaries and free surfaces, have been successfully applied to model the flow of fresh concrete in simple tests (Dufour and Pijaudier-Cabot, 2005; Cremonesi et al., 2010; Gram and Silfwerbrand, 2011; Kulesagaram et al., 2011; Ferrara et al., 2012c) as well as to a few examples of full scale castings (Roussel et al., 2007b; Cremonesi and Ferrara, 2012).

The inclusion of a dispersed fibre network in these computational tools requires peculiar issues to be taken into account. They refer to, e.g., the interaction of the wire-like particles with the suspending fluid and the other aggregates, as a function of the grading and size of these, and also of the fibre geometry and content [see Martinie (2010) for a comprehensive literature survey). The problem has been tackled also from the numerical point of view (Patankar and Joseph, 2001a, 2001b): the inclusion of solid elongated particles into the fluid phase represents the most comprehensive and reliable way to deal with the flow of SCSFRC. However, computational efforts required to deal with a large number of particles, as may be the case in true scale castings, may become huge and for this reason make the approach unpractical.

Martinie (2010) and Martinie and Roussel (2010) have recently implemented a tensor approach, based on the classical Jeffery orbit theory for the orientation process of a rotating ellipsoid immersed in an incompressible fluid. They have interestingly applied it to study the effect of the matrix rheology on the flow induced orientation of discrete (two) wire-like inclusions in a confined shear flow. Because of the computational costs of this kind of approach when applied to full scale casting processes, semi-empirical equation has been proposed by the same authors to predict the average fibre orientation factor, as a function of the concrete yield stress $\tau 0$, fibre length lf and a characteristic dimension of the casting flow. The authors have further demonstrated that, since

> "at the scale of industrial casting processes, shear induced fibre orientation is almost instantaneous phenomenon […] simple computational fluid mechanics simulations only aiming at predicting stream lines give good overviews of fibre orientation in a structural element [… and] the cartography of the stream lines through the last seconds of the casting process correlates very well with the cartography of the final fibre orientation no matter the flow history".

In this framework an attempt has been made by Ferrara et al. (2010) to correlate the orientation of the fibres to the direction of the shear rate vectors, computed through a single fluid casting flow simulation. With reference to the case study shown in Figure 3, the orientation of the fibres, as inferred from fractional conductivities measured through AC-IS [equation (2a)], has been then compared (Figure 4) to fractional orientation of the shear rate vectors, as from the CFD modelling of the casting [equation (2b)]:

$$\text{(Fractional fibre conductivity)}_{\text{x,y}} = \frac{\left[\sigma_{fibres}\right]_{\text{x,y}}}{\left[\sigma_{fibres}\right]_{\text{x}} + \left[\sigma_{fibres}\right]_{\text{y}}} \tag{2a}$$

$$\text{(Fractional Orientation)}_{\text{x,y}} = \frac{\sin\alpha_{\text{x,y}}}{\sin\alpha_{\text{x}} + \sin\alpha_{\text{y}}} \tag{2b}$$

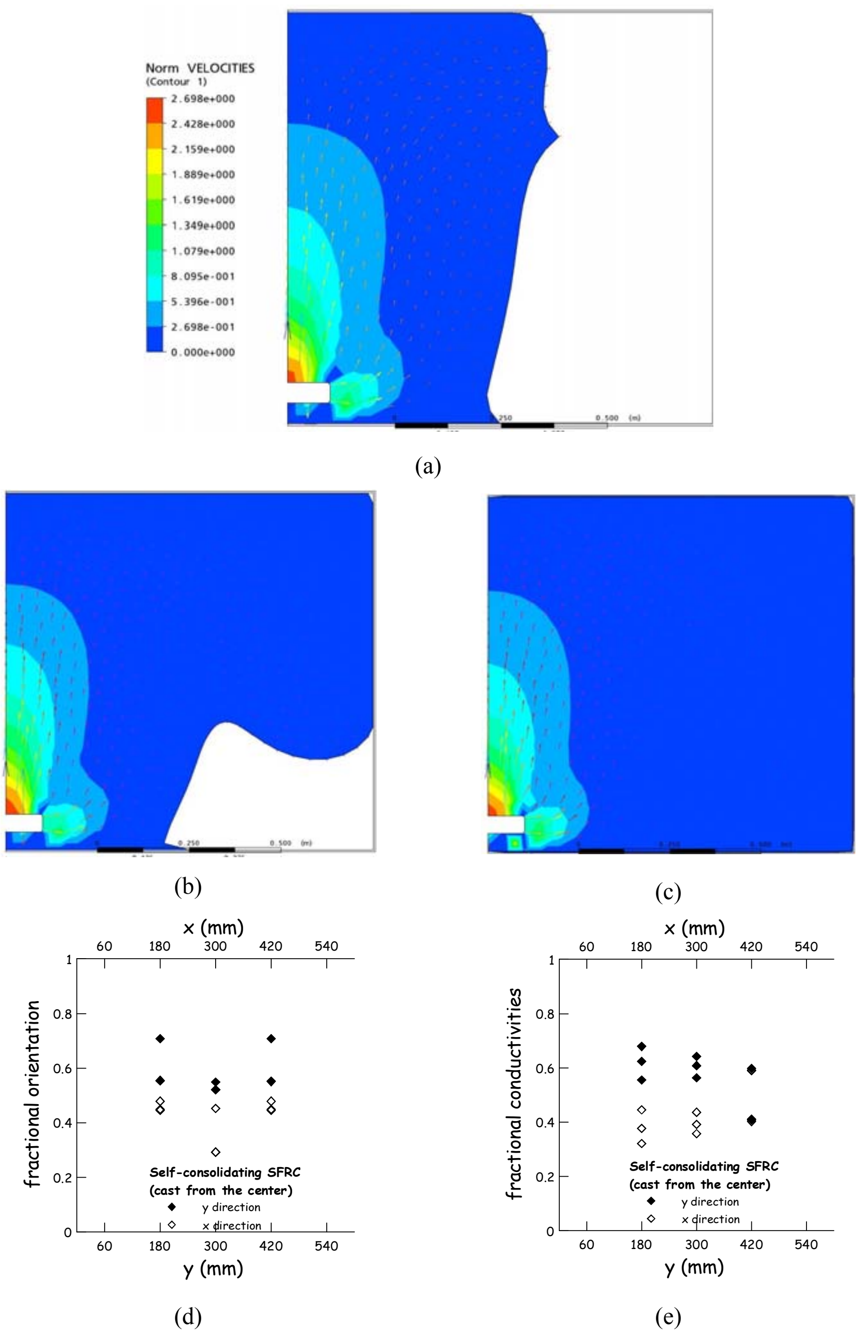
where the meaning of $[\sigma_{\text{fibres}}]$ and of $\sin\alpha$ can be got from equation (1) and Figure 4 respectively, subscripts x and y denoting alternatively the x or y direction in the plane of the cast slab.

An alternative modelling approach relies on the often made analogy between the flow of liquids and that of granular media, even though the physical properties of the two are quite different. Concrete by nature is dominated by its fluid-like behaviour or by its granular media-like behaviour according to its mix design. In the case of SCC, the amount of coarse particles in the mixture is low and this modern concrete behaves as a fluid suspension, whereas, in the case of ordinary concrete with greater amount of coarse particles, the behaviour is dominated by the granular nature of the material. Recently, it has been shown that the distinct element methods (DEM) used to simulate dry granular media flows allows for the simulation the behaviour of fresh concrete with different consistency during transport, placement and compaction (Mechtcherine and Shyshko, 2007a, 2007b, 2009). The correlation between mix design and rheology could also be investigated through the effect of the aggregate particle size distribution. Constitutive relations based on the Bingham formula were developed in order to describe the interactions between two neighbouring particles for simulating fresh concrete. In the case of the DEM fibres can be modelled as clusters of solid spheres: the number of needed particles might be very large but calculations are much faster than if fibres have to be embedded into continuum fluid modelling. A prediction has been recently proposed of the flow induced dispersion and orientation of fibres in slump-flow patties for FRCs featuring three different levels of performance in the fresh state (self-compacting, segregation-prone and vibrated) (Ferrara et al., 2012f). The experimentally detected trends, reported by Ferrara et al. (2012a) were captured with an acceptable qualitative agreement. From the quantitative point of view, some discrepancies have been detected in some of the investigated cases, which may be attributed to the employed particle generation techniques, highlighting the need for further investigation in order to fully and reliably profit of the predictive skills of the approach. Detailed information was also obtained on the distribution of fibre orientation, confirming, as detected in experiments, that in a free-surface free-front flow fibres tend to align, also as a function of concrete rheology, transverse to the flow itself (Barnett et al., 2010; Boulekbache et al., 2012).

5 Concluding remarks

This paper has reviewed, in the context of the international state of the art, the main findings of the research activity performed by the author in the last lustrum, with reference to the correlation among fresh state performance, fibre dispersion and mechanical properties of fibre reinforced cementitious composites with adapted rheology and the methods and tools for non-destructive monitoring and prediction of fibre dispersion and orientation. Part 2 paper will hence focus on the effects of flow induced orientation of fibres on the mechanical properties of the composite and will highlight its outcomes in terms of structural design of engineering applications. More general conclusions will be addressed and a view will be forecast over future research needs and developments.

Figure 5 CFD modelling of casting a SFRSCC plate (cast from the centre – modelling one quarter of the plate shown in Figure 3), (a–c) sequence of formwork filling with velocity field highlighted, comparison between fractional orientation from flow (d) cartography through equation (2b) and (e) fractional conductivities from AC-IS measurements through equation (2a) (see online version for colours)



Source: Ferrara et al. (2010)

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