Tailoring the orientation of fibres in high performance fibre reinforced cementitious composites: part 2 – correlation to mechanical properties and design implications

Liberato Ferrara

Department of Civil and Environmental Engineering,
Politecnico di Milano,
Piazza Leonardo da Vinci 32,
20133 Milan, Italy
Email: liberato.ferrara@polimi.it

1 Introduction

In the last decade fibre reinforced cementitious composites with adapted rheology and superior fresh state performance, such as fibre reinforced self-compacting concrete (FR-SCC) have been used in several partially and fully structural applications, including slabs on grade (Groth and Nemegeer, 1999), overlays (Carlsward and Emborg, 2007), precast pre-stressed beams (Dhonde et al., 2007) and roof elements (Ferrara and Meda, 2006), sheet piles, tunnel segments (Grunewald, 2004), precast post-tensioned girders for slope stabilisation (Di Prisco et al., 2006), panel and slab housing units (Barragàn et al., 2004; Borralleras et al., 2007), refractory linings in industrial equipments (Romano et al., 2007) and façade panels (Bigas et al., 2007; Pereira et al., 2007).

As mentioned in the introduction to part 1 of the paper, incorporating fibres into a self-compacting concrete (SCC) matrix, can lead to a better dispersion and, in case, to a tailored orientation of the fibres. This would lead to a superior mechanical and structural performance which can also result into optimised structure size and reduced self weights. Benefits may also follow in terms of time- and cost-effectiveness of the construction process as a whole, including, e.g. in the case of precast elements, costs for transportation, lifting equipments etc.

It is furthermore evident that the synergy between the technologies of SCC and fibre reinforced concrete (FRC) can improve the economic efficiency of the construction process: reduced construction time, reduced work force, reduced energy consumption, better working environment with reduced noise and health hazards, and enhanced automation of the quality-control process, thanks – among other factors – to the reduction of the ordinary reinforcement and to the simplification of reinforcement detailing and placing. This clearly highlights that FR-SCC favours sustainability as well.

As a matter of fact the influence of the flow-driven fibre dispersion and orientation on the mechanical performance represents a key distinctive feature of self-compacting FRC as compared to traditional vibrated FRC, which cannot be disregarded when analysing engineering and mechanical properties of the material. To this aim, a thorough understanding is required of the mechanisms underlying the connection between mix-design and fresh state performance, on one hand, and the dispersion and orientation of the fibres on the other hand, also in the context with monitoring and prediction to achieve the anticipated performance in the hardened state.

The design approach proposed in the recently issued final version of Model Code 2010 recommends each fibre reinforced cementitious composite to be regarded as a macroscopically homogeneous material, with its own properties. These have to be identified through suitable test procedures which have obviously to 'reproduce' the aforementioned synergistic effect between matrix and fibres, consistently with the performance requested to the material by the intended structural application. Moreover, the test procedures have to take into account issues related to the production process, as affected by the fresh state performance and the structure geometry and as affecting the dispersion and orientation of the fibres with respect to the stress state to be applied.

This second part of the paper will review in the aforementioned framework, the engineering and mechanical properties of highly flowable/self-compacting, as a function of the flow induced orientation of the fibres. The main research needs will be addressed which still challenge the wide development of engineering and structural applications with this category of advanced cement-based materials.

2 Implications on material and structural performance and design

Mechanical properties of fibre reinforced cementitious composites are actually the outcome of a synergy between the properties of the concrete matrix and the toughening effect exerted by the dispersed wirelike reinforcement. This effect depends on the geometry and dosage of the fibres, strength of the filament, fibre dispersion and orientation with respect to the applied stress and on the fibre-matrix bond. Approaches aimed at predicting the mechanical response of FRCs from pull-out behaviour of single fibres and fibre distribution data (Armelin and Banthia, 1997) have received renewed attention in the last years (Jones et al., 2008; Cunha et al., 2010; Laranjeira et al., 2010a, 2010b, 2011). The previously recalled advances in non-destructive fibre dispersion monitoring techniques allowed valuable database to be effectively garnered for validating these approaches.

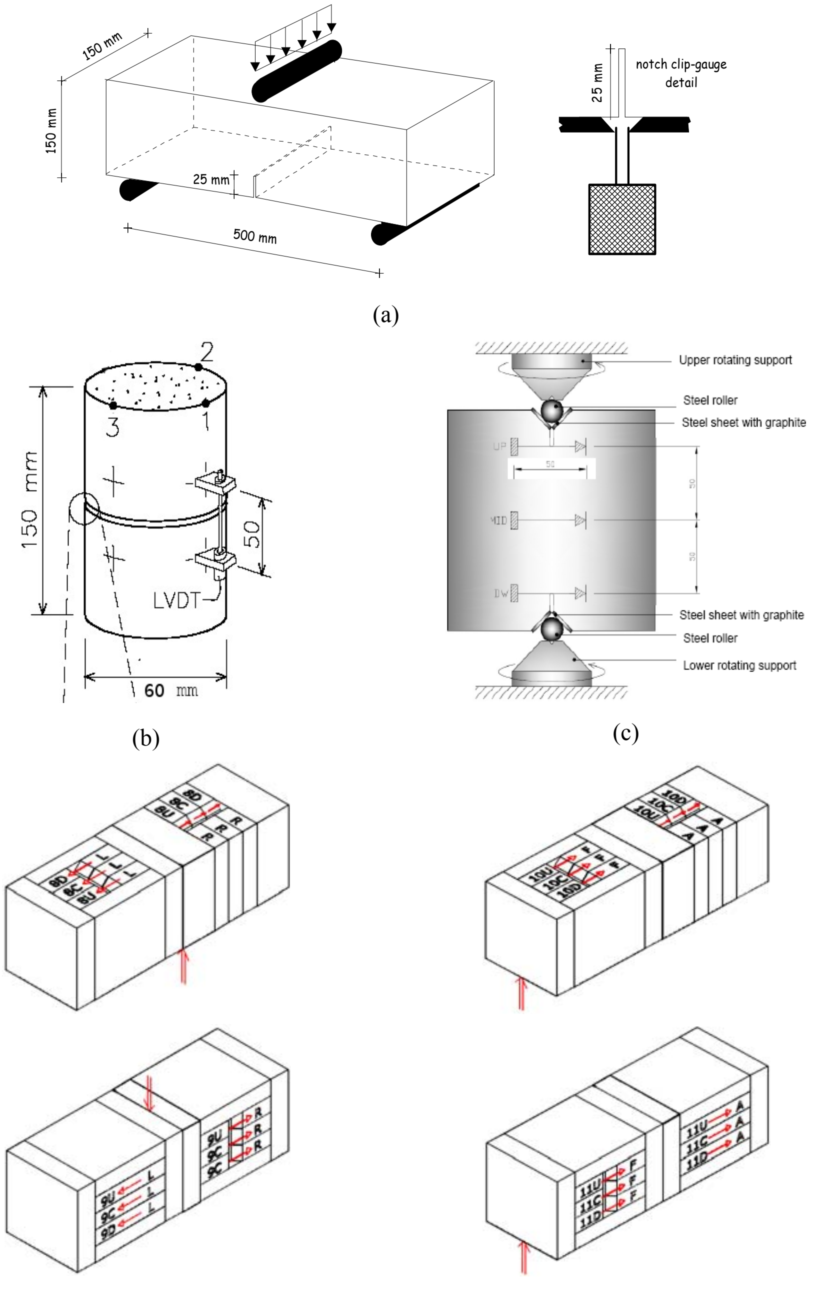
The influence of the production process, as affected by the fresh state performance and the structure geometry and as affecting the dispersion and orientation of the fibres with respect to the stress state to be applied, has to be duly taken into account into experimental procedures for the identification of material properties as well as into structural design approaches.

This, on one hand, requires an ‘engineering toolbox’ to be ‘created’ and validated for the prediction of fibre orientation in practical applications of FRCCs, as the outcome of the effects of material properties and issues related to production processes. Furthermore the need has to be highlighted of integrating, into the concept and design of structures made with advanced concretes and cementitious composites, such as FR-SCC, material properties, production processes and the geometry and function of the structure itself. In this way both the material and the production processes can be effectively tailored to the intended structural application (Laranjeira et al., 2012).

Table 1 Mix design of FRCs employed in investigation detailed in Ferrara et al. (2012b)

Mix-constituent	*Dosage (kg/m^3)*
Cement type 42.5	472
Fly ash	45
Water	216 (w/b = 0.42)
Superplasticiser	6 (lt/m^3)
Sand 0–4 mm	850
Gravel 4–8 mm	886
Steel fibres 65/35	50

Figure 1 Designing with fibre orientation, (a) scheme of experimental specimens and set-up for 3pb tests, (b) dews test and (c) direct tension test, (d) cutting scheme to obtain dews specimens from beams,(e) constitutive FRC parameters vs. fibre orientation on fracture surface, evaluation of orientation factors from statistical processing of constitutive parameters for (f) SLS and (g) ULS (see online version for colours)



(a)

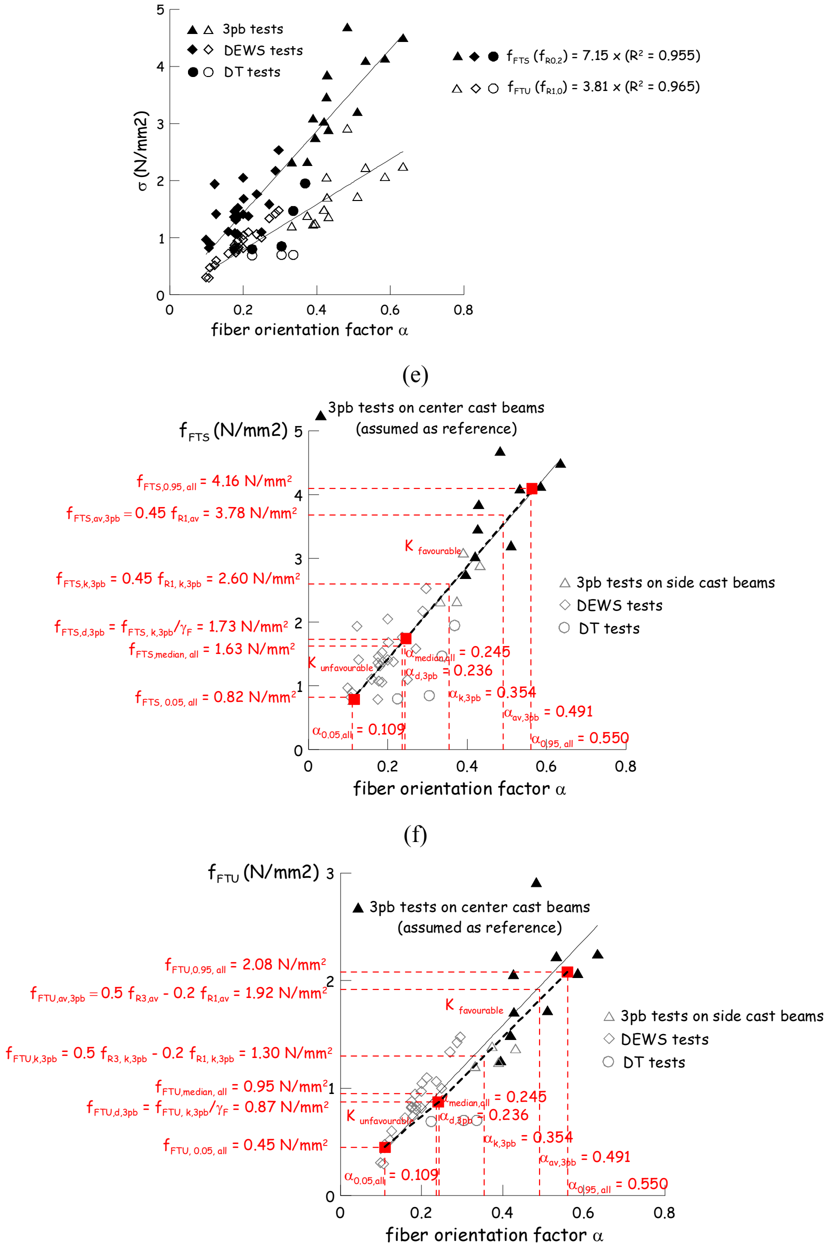
(b)

(c)

(d)

Source: Ferrara et al. (2012b)

Figure 1 Designing with fibre orientation, (a) scheme of experimental specimens and set-up for 3pb tests, (b) dews test and(c) direct tension test, (d) cutting scheme to obtain dews specimens from beams,(e) constitutive FRC parameters vs. fibre orientation on fracture surface, evaluation of orientation factors from statistical processing of constitutive parameters for (f) SLS and (g) ULS (continued) (see online version for colours)



(g)

Source: Ferrara et al. (2012b)

In an attempt to address the aforementioned issue, Ferrara et al. (2012b) have investigated the effects of fibre orientation factor on the statistical dispersion of the parameters defining the tensile constitutive relationship of a self compacting steel FRC (mix design detailed in Table 1). Mechanical parameters were identified from the results of three point bending tests on notched specimens, performed according to EN 14651 [Figure 1(a)]. Thirteen beams were tested: in order to induce different flow induced orientation of fibres on the ligament, different casting procedures were adopted when preparing the specimens.

Nine beams were cast from the centre whereas the remaining four were cast from one side. From one beam cast from the centre, separated into two halves at the end of the bending tests, 60 mm cylinder specimens were cored, from which four 60mm long specimens for direct tension tests were obtained. Specimens were circumferentially notched up to a ligament net section 50 mm in diameter and tested in direct tension (see Figure 1(b) for specimen geometry and test set-up).

In order to increase the number of possible combinations between the alignment of fibres, induced by the casting flow, and the direction of the tensile stress applied during the test, 150 × 150 mm square tiles, 50 mm thick, were cut from two beams cast from the centre and two cast from the side [Figure 1(d)]. The tiles were further 'processed' in order to obtain the final geometry shown in Figure 1(c), suitable to perform the so-called 'double edge wedge splitting' (DEWS) tests (Di Prisco et al., 2013) [details of the test set-up are also shown in Figure 1(c)]. According to this novel testing technique the applied compressive load is converted, thanks to the wedge shaped grooves which accommodates the loading device, into an indirect transverse tensile force across the ligament. Furthermore, unlikely than what happens in Brazilian splitting tests, the trajectory of principal compressive stresses is always kept aside from the ligament, along which a pure mode I fracture process is thus induced, without any disturbance from, e.g., a compressive stress state at a right angle to it (Ferrara and Di Prisco, 2011). The cutting procedure was such that the notch preordained fracture plane (ligament) in DEWS specimens were characterised by different orientations to the main direction of flow when casting prism specimens [Figure 1(d)], which was, most likely, correlated to the flow induced orientation of the fibres, as remarked above.

Residual tensile stresses at prescribed crack opening values were either directly calculated or back identified from the results of direct/indirect tensile and bending tests respectively. The crack opening thresholds for direct and indirect tensile tests were chosen in such a way to have the same strain as for the CMOD thresholds prescribed by the standards for residual stresses identified from bending tests (see Ferrara et al., 2012a). Plots in Figure 1(e), in which stresses corresponding to the aforementioned strain levels from all the performed tests have been grouped together, clearly confirms the reliability of the proposed interpretative criterion. At the same time they highlight the importance of the flow-induced orientation of fibres, even in casting, small specimens' for a consistent identification of the tensile behaviour of FR-SCC.

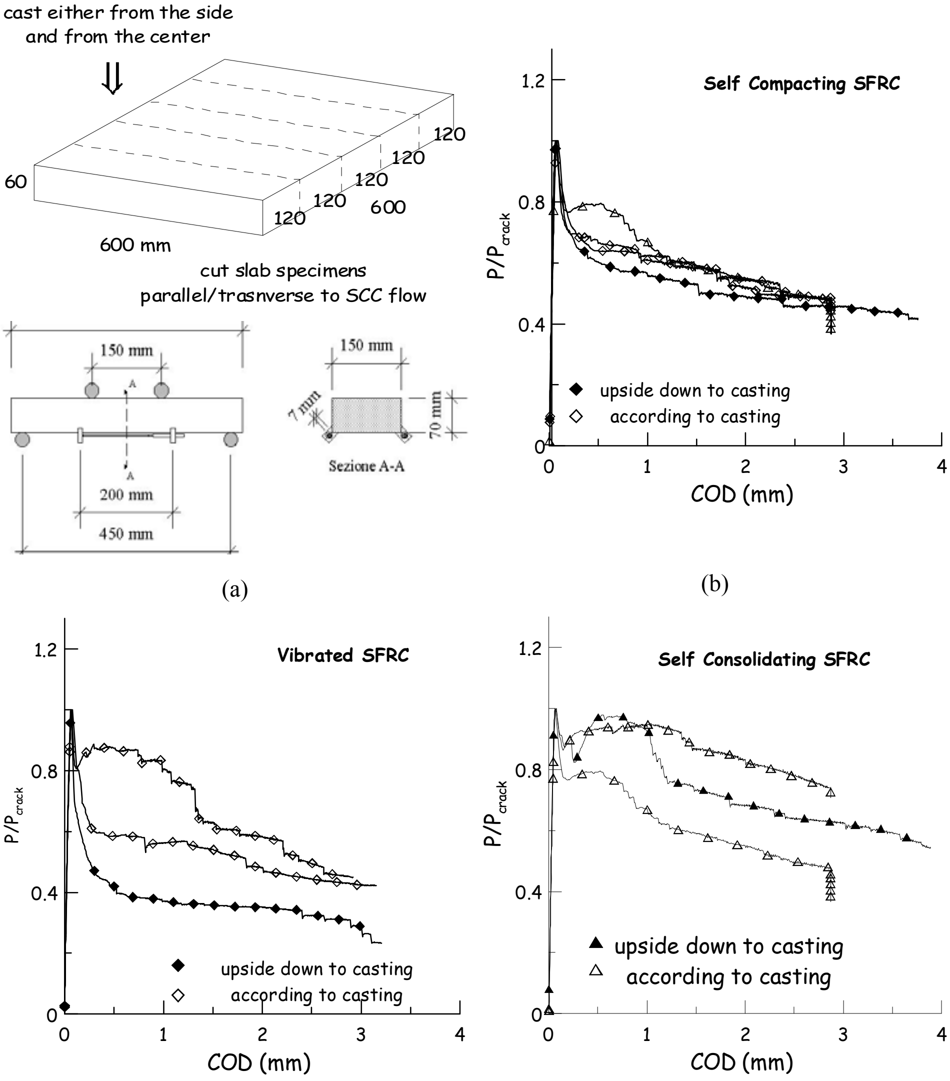
The results also provide a tool for rational evaluation of the effects of the flow induced fibre orientation on the identified values of 'true' material residual stresses. The wide set of experimental tests performed, even with different modalities and set-ups as well as the different ways of obtaining, either by casting or cutting, the testing samples, has allowed a broad range of orientation factors over the fracture cross sections of tested specimens to be obtained, precisely between 0.1 and 0.63. Interestingly, these values are close to upper and lower bound for fibre orientation even for strongly orientated casting flow (Ferrara et al., 2011).

In the framework of the Model Code 2010 approach, the aforementioned database makes it possible to evaluate to which extent either a favourable or unfavourable orientation of the fibres can affect the values of representative post-cracking residual stresses, as identified through back analysis from the results of bending tests. The results of this procedure are summarised in Figures 1(f)–6(g). Because of the strong correlation existing between material toughness and fibre orientation on the fracture surface of tested beam specimens, the shifting from the average to the characteristic to the design value is equivalent to a downward shift towards a fibre orientation less favourable than the random one. As a matter of fact this coincides with the median value of the whole set of orientation values which were obtained in this investigation over about 40 experimental values, obtained from both direct and indirect (bending and DEWS) tests. Upper and lower bounds for a 'fibre orientation factor' were hence calculated as the upper and lower 5% fractiles of the whole set of fibre orientation factors, or, equivalently, of related values of material residual stresses at representative COD levels. This resulted in a factor, by which the design values of material properties have to be divided to take into account the effects of an unfavourable or favourable orientation of fibres, respectively equal to 2 and 0.4. These values can hence be regarded as representative of a broad range of flow induced orientation of fibres as obtainable in real casting.

In the same framework described above, Ferrara et al. (2008) already analysed the correlation between the fresh state performance and the dispersion of the material properties inside a structural element. They tested beams cut from the same slabs, made with FRCs featuring different levels of fresh state performance (see Table 2 – part 1 of this paper), as shown in Figure 2. The higher robustness of the SFR-SCC performance clearly appears, together with its higher resistance to fibre segregation, and was likewise clearly attributable to the better fibre dispersion achieved (see Figure 3 in part 1 of this paper, referring to the same investigation).

More recently, Ferrara et al. (2012b) have also attempted, with reference to a SFR-SCC conceived for precast pre-stressed roof elements, to investigate the correlation between the different indicators of the fresh state performance (slump flow diameters and times, V-funnel flow time) and: on one hand the expected spatial dispersion of the fibres, in lab specimens and full size castings. On the other, the expected spatial dispersion of the toughness properties of the FRC composite was quantified through equivalent post-cracking stresses at different crack opening thresholds, as a function of the different levels of fresh state performance. These were obtained by varying the cement or water of SP content in the mix design listed in Table 1. The results, a selection of which is shown in Figure 3, have highlighted the importance of governing the aforementioned correlation in order to avoid, through a suitable performance in the fresh state and a tailored casting process, the lack of homogeneity in the spatial dispersion of material properties inside a structural element, as cast. This lack of homogeneity could easily jeopardise the performance of the element itself. In this perspective, indicators of fresh state performance also acquire a new significance, since their acceptable values could be calibrated to assess an educated guess about the expectable 'in structure' spatial dispersion of material properties.

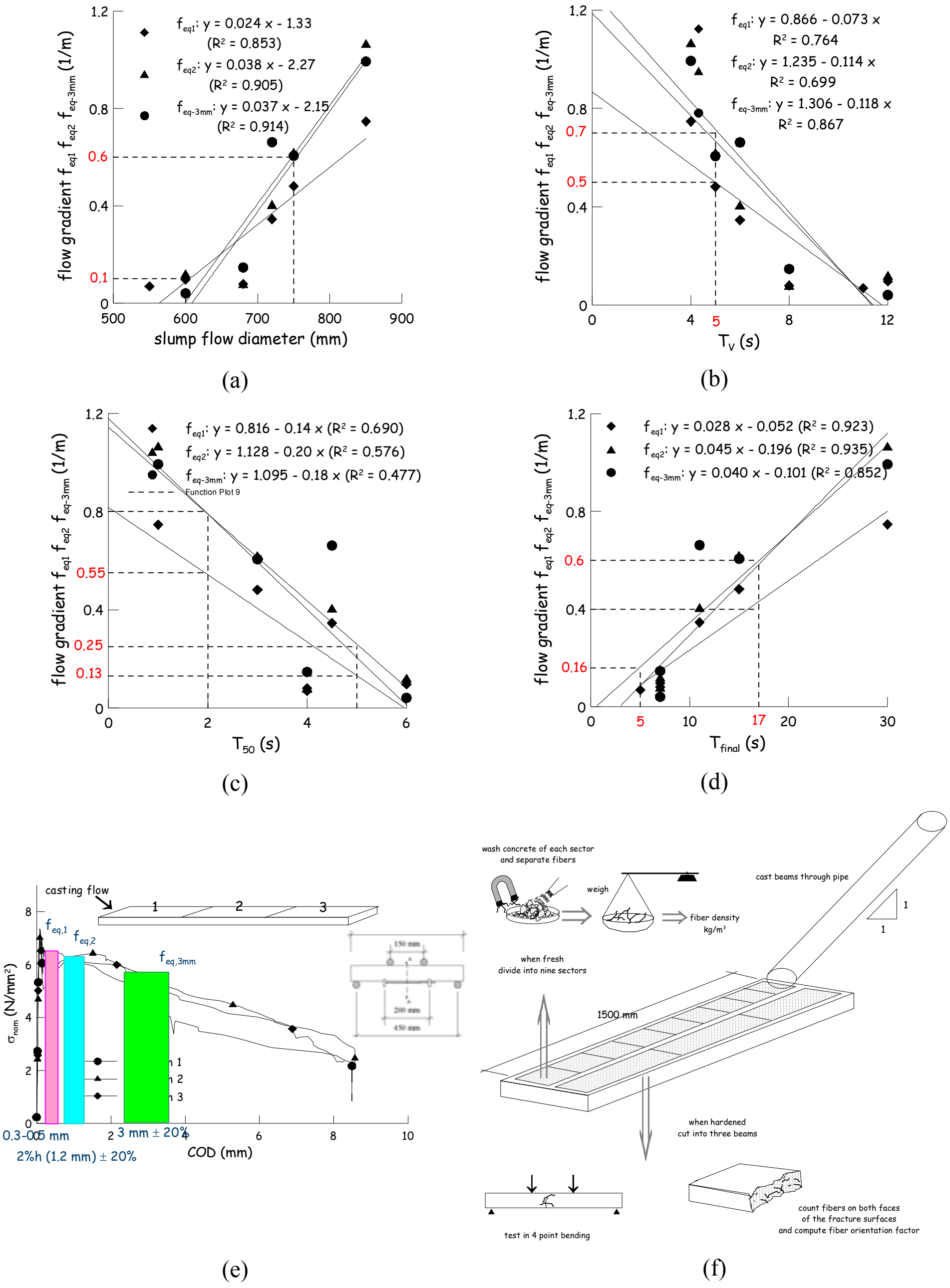
Figure 2 Correlation of fresh state performance and mechanical properties in the hardened state, (a) scheme for beam cutting from slabs and 4pb test set-up, normalised load vs. cod for (b) vibrated, (c) self-consolidating, and (d) segregation prone SFRC


(a) (b) (c) (d)

Source: Ferrara et al. (2008)

The outcomes, in terms of structural performance, of the aforementioned flow-induced alignment of fibres, as achievable by means of a casting process tailored to the same performance of the intended application, can be straightforwardly assessed in the case of beam, or beam-like, elements.

Figure 3 ‘Spatial’ coefficients of variation of FR-SCC toughness indices vs. indicators of fresh state performance (a–d) [T50 and Tfinal denote the time to 500 mm spread and time to final spread measured from slump flow tests; tv denotes the slump flow time]; feq,1, feq,2, and feq,3mm denote post-cracking equivalent stresses at 0.4 mm, 1.2 mm and 3 mm crack opening respectively as shown in (e); tests were made on 60 mm thick specimens obtained from longer beams casted and processed as shown in (f) (see online version for colours)



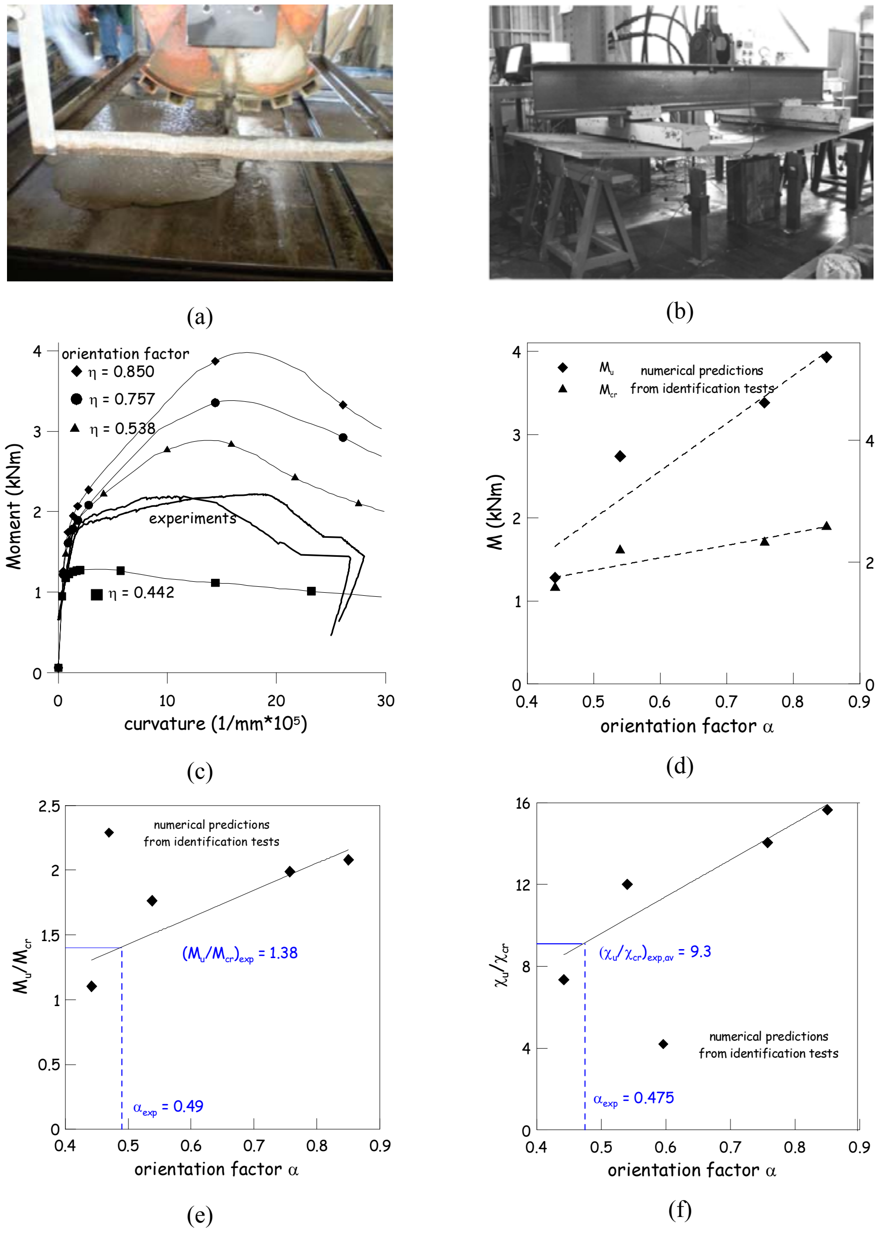
(a) (b)

(c) (d)

(e) (f)

Source: Ferrara et al. (2012a)

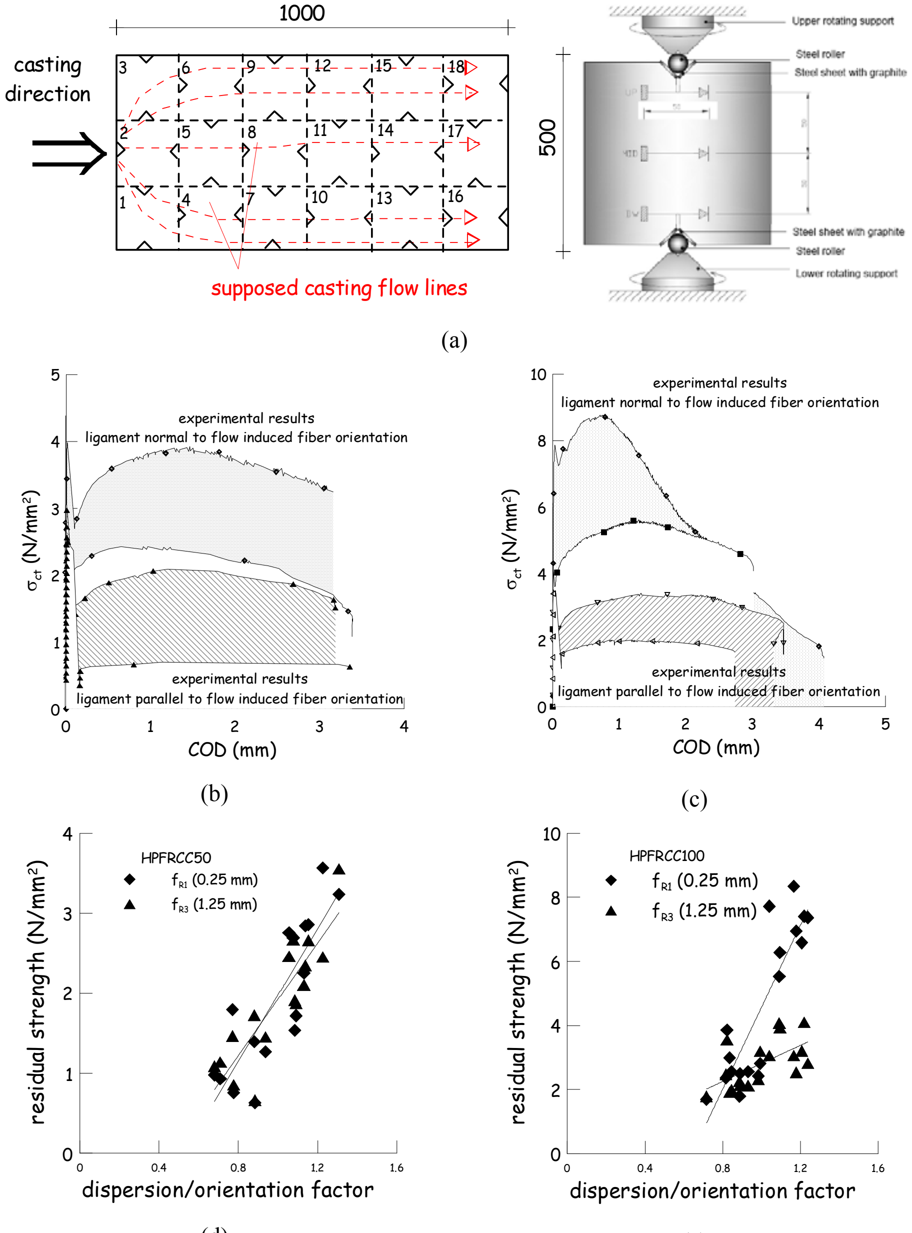
Figure 4 Casting a (a) HPFRCC slab and (b) 4pb testing scheme; (c – identification as in Figure 2, part 1 of this paper) experimental results and prediction of behaviour for favourable vs. unfavourable fibre orientation; effect of fibre orientation (d) on cracking moment M_{cr} and ultimate moment M_u, (e) on post-cracking strength resources M_u/M_{cr} and (f) on ductility χ_u/χ_{cr} (see online version for colours)



Note: Numerical predictions from identification tests and experimental results from true scale tests.

Source: Ferrara et al. (2010, 2012c)

Figure 5 Influence of fibre orientation on SC-HPFRCCS [5, 6], (a) scheme of casting and specimen cutting and test set up for indirect tensile tests (dews), tensile stress vs. crack opening curves for (b) HPFRCC-50 and (c) HPFRCC-100 and correlation of residual tensile stresses at different crack openings (0.25 and 1.25 mm) to fibre dispersion/orientation factors from (d) magnetic and (e) monitoring (see online version for colours)



(a)

(b)

(c)

(d)

(e)

Source: Ferrara et al. (2012d)

The prevalent bending action along the longitudinal axis of the beam unambiguously implied the direction of the principal tensile stresses. On the other hand, this kind of elements, because of their geometry, can easily be cast in such a way that the direction of flow of the fresh concrete, along which the preferential alignment of fibres can be achieved, can easily match with the aforementioned direction of principal tensile stress.

The same occurs for slab elements which are intended and designed to work as beams along their major span. Di Prisco et al. (2008) presented the case study of thin precast roof slabs, 2.5 m long, 1.2 m wide and 25 mm thick, made out with no conventional reinforcement and with the same self-levelling high performance fibre reinforced cementitious composite (HPFRCC) presented in Sections 2 and 3 of this paper with reference to lab scale investigations (mix designs summarised in Table 1 – part 1 of this paper). The slabs have been designed to work as simply supported beams along their main span. A numerical prediction of the structural performance based on the results of the investigations detailed in previous sections (see Figures 2 and 4 in part 1 of this paper), clearly highlights the benefits in terms of load bearing capacity and ductility (Figure 4) which could be achieved through tailored casting and resulting fibre alignment, with respect to the ‘random cast’ case, tested in the case study project.

As a matter of fact, among the earliest pioneer applications of HPFRCCs, thin shell structures can be listed (Vicenzino et al., 2005), merging into a unique high value architectural shape and structural function. In this kind of structures, unlike beams, the material undergoes membrane biaxial stress states, which have to be carefully matched with a tailored alignment of the fibres. This, in fact, if enhancing the performance the material when stressed along the same direction, also makes it quite poorer along the direction orthogonal to it. Ferrara et al. (2011, 2012d) have in fact recently demonstrated that not only the fibre orientation affects, as expectable and as well assessed, the post-cracking toughness of the material, but also that the same material can exhibit either a strain hardening or a strain softening behaviour, whether stressed parallel or orthogonally to the flow-aligned fibres (Figure 2 – part 1 of this paper and Figure 5). This flow-induced anisotropy can be the outcome of an integrated material, processing and structural design, as this paper aims to demonstrate. In this respect it has to be carefully handled with in structural analysis and modelling, and also experimentally characterised by means of dedicated procedures (see, e.g., Suryanto et al., 2010), which cannot disregard the specific structural application the material and the casting process have been conceived to.

This issue becomes even more important when stress reversal can be expected, e.g., because of earthquake action. The anisotropic behaviour of the material recalled above can hence result in a non-symmetric cyclic response of structures made of and/or retrofitted with HPFRCCs, the latter field of application being highly promising (Martinola et al., 2010). In this framework, the effects of the flow induced anisotropy on the cyclic behaviour of the material need to be experimental characterised, in terms, e.g., of load bearing capacity degradation, stiffness recovery and degradation, cyclic energy dissipation capacity. The garnered knowledge has to be transferred into effective material models for a reliable prediction of the structural response. This stands, so far, in the author’s opinion, among the most urgent research needs to be tackled in order to further reliably promote the aforementioned applications of HPFRCCs and develop likewise reliable and consistent design procedures.

3 Concluding remarks

This paper and its companion part 1 have reviewed, also in the context of the current international state of the art and research and application perspective, the main findings of the research activity performed by the author in the last lustrum, with reference to the correlation among the fresh state performance, the fibre dispersion and the mechanical properties of fibre reinforced cementitious composites with adapted rheology and the possibility of governing the aforementioned correlations to conceive, design and build high end engineering and structural applications employing this category of advanced cementitious composites.

The following conclusions can be highlighted:

- Tailored alignment of fibres in structural elements made with self compacting/highly flowable fibre reinforced cementitious composites can be obtained, also as a function of the geometry of the element, owing to the superior fresh state performance of the material and as the outcome of a suitably designed casting process.
- Methods for non-destructive monitoring of fibre dispersion in full scale castings have been developed by several researchers worldwide and are, in the author's opinion, ready to be exported from university labs into the construction practice.
- Tools to design the casting process and predict through it the most likely alignment of the fibres are still at an embryonic stage, most likely because of the high computational time still required to have meaningful information for a real scale casting flow simulation. Interesting results, also from the quantitative point of view in terms of predicted vs. measured dispersion and orientation of the fibres, have been by the way obtained for small volume castings. Furthermore simple empirical formulations and heuristic approached have been developed and calibrated on wide and sound experimental databases. They represent the first step for the effective embedment of casting design and fibre orientation predictive tools into an integrated design framework for structural elements made with highly flowable FRCs.

With reference to the latter, which is a relatively new and cutting edge research concept, this paper has reviewed the main results achieved with reference to a fibre orientation dependent procedure for the identification of design material properties of FRCs, coherently with current design approaches. Furthermore some challenging and cutting edge research needs have been highlighted. They refer to the experimental characterisation and modelling of the 'flow induced' anisotropy of the material behaviour, under both static and cyclic loadings, which have to be urgently tackled also in the sight of emerging applications of this category of advanced cement-based composites.

The possibility of governing the correlation among fresh state performance, fibre dispersion and orientation of fibre reinforced cementitious composites would lead to the concept of an integrated 'holistic' design approach 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 element when in service, so to achieve a more efficient structural use of the material. A closer correspondence between the shape of an element and the function it performs in a structure assembly could thus be achieved. A suitably balanced fresh-state performance 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.

Acknowledgements

I wish to express my gratitude to my mentors, Prof. G. Toniolo and Prof. Marco di Prisco, who addressed my research towards fibre reinforced cementitious composites, and prof. S.P. Shah, who, during my stay at the Centre for Advanced Cement-based Materials, Northwestern University, transmitted to me his attitude towards interdisciplinary and collaborative research which has inspired my work since then. The contribution of Fulbright Foundation for funding my research at ACBM is also gratefully acknowledged.

The work illustrated in this paper could have not been done without the collaborative enthusiasm of several colleagues and friends: Prof. R. Ottoboni, Assistant Professors M. Faifer, P. Bamonte and S. Toscani, Dr. A. Caverzan, Dr. M. Cremonesi and Dr. M. Lamperti, Politecnico di Milano; Prof. V. Mechctcherine, Technical University of Dresden, Germany, Prof. Y.D. Park, Daegu Haani University, South Korea and Prof. N. Ozyurt, Bogazici University, Turkey. A special thanks also to my PhD student Milot Muhaxheri and to all the graduate and undergraduate students who shared with me the passion for these awe-inspiring advanced construction materials.

References

Armelin. H.S. and Banthia, N. (1997) 'Predicting the flexural post-cracking performance of steel fibre reinforced concrete from the pullout of single fibers', *ACI Materials Journal*, Vol. 94, No. 1, pp.18–31.

Barragàn, B., Zerbino, R., Gettu, R., Soriano, M., de la Cruz, C., Giaccio, G. and Bravo, M. (2004) 'Development and application of steel fiber reinforced self-compacting concrete', in Di Prisco, M. et al. (Eds.): *BEFIB 2004, Proceedings 6th International RILEM Symposium*, Varenna, Italy, 20–22 September 2004, Rilem Pubs., pp.455–464.

Bigas, J.P., Pellerin, B., Deschryver, F., Massinari, P. and Plizzari, G. (2007) 'Syntetic macro-fibers reinforced self compacting concrete for lightweight precast elements. A case study', in De Schutter, G. and Boel, V. (Eds.): *Proceedings SCC2007, 5th International RILEM Symposium on Self-Compacting Concrete*, 3–5 September 2007, Gent, Belgium, Rilem Pubs, pp.1013–1018.

Borralleras, P., Barragàn, B. and Gettu, R. (2007) 'Comparison for durability parameters between conventional concrete standard SCC and Steel Fibre Reinforced SCC for construction of thin elements. Part 2: thin concrete walls application', in De Schutter, G. and Boel, V. (Eds.): *Proceedings SCC2007, 5th International RILEM Symposium on Self-Compacting Concrete*, 3–5 September 2007, Gent, Belgium, Rilem Pubs, pp.1092–1098.

Carlsward, C. and Emborg, M. (2007) 'Shrinkage cracking of steel fibre reinforced self compacting concrete overlays – tests methods and theoretical modelling', in De Schutter, G. and Boel, V. (Eds.): *Proceedings SCC2007, 5th International RILEM Symposium on Self-Compacting Concrete*, 3–5 September 2007, Gent, Belgium, Rilem Pubs, pp.793–798.

Cunha, V.M.C.F., Barros, J.A.O. and Sena-Cruz, J.M. (2010) 'Pull.out behavior of steel fibers in SCC', *ASCE Journal of Materials in Civil Engineering*, Vol. 22, No. 1, pp.1–9.

Dhonde, H.B., Mo, Y.L., Hsu, T.T.C. and Vogel, J. (2007) 'Fresh and hardened state properties of self-consolidating fiber-reinforced concrete', *ACI Materials Journal*, Vol. 104, No. 5, pp.491–500.

Di Prisco, C., Di Prisco, M., Mauri, M. and Scola, M. (2006) 'A new design for stabilizing round slopes', *Proceedings of the 2nd World fib Congress*, Naples, 2–5 June 2006 (paper 823-CD-Rom).

Di Prisco, M., Ferrara, L. and Lamperti, M.G.L. (2013) 'Double Edge Wedge Splitting (DEWS): an indirect tension test to identify post-cracking behaviour of fibre reinforced cementitious composites', *Materials and Structures*, Vol. 46, No. 11, pp.1893–1918, doi 10.1617/s11527-013-0028-2.

Di Prisco, M., Lamperti, M.G.L., Lapolla, S. and Khurana, R.S. (2008) 'HPFRCC thin plates for precast roofing', *Proceedings 2nd International Symposium on HPC*, Kassel, March 2008.

Ferrara, L. and Di Prisco, M. (2011) 'The role of fiber orientation on strain gardening/softening FRCCs: continuum damage modelling', in Toledo Filho, R.D. et al. (Eds.): *Proceedings SHCC2 2nd RILEM International Conference on Strain Hardening Cementitious Composites*, Rio de Janeiro, Brasil, 12–14 December, RILEM Pubs. PRO 81, pp.79–88.

Ferrara, L. and Meda, A. (2006) 'Relationships between fibre distribution, workability and the mechanical properties of SFRC applied to precast roof elements', *Materials and Structures*, Vol. 39, No. 4, pp.411–420.

Ferrara, L., Bamonte, P., Caverzan, A., Musa, A.M. and Sanal, I. (2012a) A comprehensive methodology to test the performance of steel fibre reinforced self-compacting concrete (SFR-SCC)', *Construction and Building Materials*, Vol. 37, pp.406–424.

Ferrara, L., Caverzan, A., Muhaxheri, M. and Di Prisco, M. (2012b) 'Identification of tensile behaviour of SFR-SCC: direct vs. indirect tests', Accepted for presentation to *BEFIB2012*.

Ferrara, L., Faifer, M. and Toscani, S. (2012c) 'A magnetic method for non destructive monitoring of fiber dispersion and orientation in steel fiber reinforced cementitious composites – part 1: method calibration', *Materials and Structures*, Vol. 45, No. 4, pp.575–589.

Ferrara, L., Faifer, M., Muhaxheri, M. and Toscani, S. (2012d) 'A magnetic method for non destructive monitoring of fiber dispersion and orientation in steel fiber reinforced cementitious composites – part 2: correlation to tensile fracture toughness', *Materials and Structures*, Vol. 45, No. 4, pp.591–598.

Ferrara, L., Ozyurt, N. and di Prisco, M. (2011) 'High mechanical performance of fiber reinforced cementitious composites: the role of "casting-flow" induced fiber orientation', *Materials and Structures*, Vol. 44, No. 1, pp.109–128.

Ferrara, L., Park, Y.D. and Shah, S.P. (2008) 'Correlation among fresh state behaviour, fiber dispersion and toughness properties of SFRCs', *ASCE Journal of Materials in Civil Engineering*, Vol. 20, No. 8, pp.493–501.

Groth, P. and Nemegeer, D. (1999) 'The use of steel fibres in self-compacting concrete', *Proceedings 1st International Rilem Symposium on Self-Compacting Concrete*, pp.497–507.

Grunewald, S. (2004) *Performance-Based Design of Self Compacting Steel Fiber Reinforced Concrete*, PhD Thesis, Delft University of Technology.

Jones, P.A., Austin, S.A. and Robis, P.J. (2008) 'Predicting the flexural load-deflection response of steel fibre reinforced concrete from strain, crack-width, fibre pull-out and distribution data', *Materials and Structures*, Vol. 41, No. 3, pp.449–463.

Laranjeira, F. Aguado, A., Molins, C., Grunewald, S, Walraven, J and Cavalaro, S. (2012) 'Framework to predict the orientation of fibers in FRC: a novel philosophy', *Cement and Concrete Research*, Vol. 42, No. 6, pp.752–768.

Laranjeira, F., Aguado, A. and Molins, C. (2010a) 'Predicting the pullout response of inclined straight steel fibers', *Materials and Structures*, Vol. 43, No. 6, pp.875–895.

Laranjeira, F., Molins, C. and Aguado, A. (2010b) 'Predicting the pullout response of inclined hooked steel fibers', *Cement and Concrete Research*, Vol. 40, No. 10, pp.1471–1487.

Laranjeira, F., Grunewald, S., Walraven, J., Blom, C., Molins, C. and Aguado, A. (2011) 'Characterization of the orientation profile of steel fiber reinforced concrete', *Materials and Structures*, Vol. 44, No. 6, pp.1093–1111.

Martinola, G., Meda, A., Plizzari, G.A. and Rinaldi, Z. (2010) 'Strengthening and repair of RC beams with fiber reinforced concrete' *Cement and Concrete Composites*, Vol. 32, No. 9, pp.731–739.

Pereira, E.N.B., Barros, J.A.O., Ribeiro, A:F. and Camoes, A. (2007) 'Post-cracking behaviour of self compacting steel fibre reinforced concrete', in Di Prisco, M. et al. (Eds.): *BEFIB 2004, Proeedings 6th International RILEM Symposium*, Varenna, Italy, 20–22 September. 2004, Rilem Pubs., pp.1371–1380.

Romano, G.Q., Silva, F.A., Toledo Filho, R.D., Fairbairn, E.M.R. and Battista, R.C. (2007) 'Mechanical characterization of steel fiber reinforced self-compacting refractory concrete', in De Schutter, G. and Boel, V. (Eds.), *Proceedings SCC2007, 5th International RILEM Symposium on Self-Compacting Concrete*, 3–5 September 2007, Gent, Belgium, Rilem Pubs, pp.881–886.

Suryanto, B., Nagai, K. and Maekawa, K. (2010) 'Bidirectional multiple cracking tests on high performance fibre reinforced cementitious composite plates', *ACI Materials Journal*, Vol. 107, No. 5, pp.450–460.

Vicenzino, E., Culham, G., Perry, V.H., Zakariasen, D and Chow, T.S. (2005) 'First use of UHPFRC in thin precast concrete roof shell for Canadian LRT station', *PCI Journal*, Vol. 50, No. 5, pp.50–67.