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A discussion paper of fib TG 8.8

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Translation of test results of small specimens of flowable fibre concrete to structural behaviour, a discussion paper of fib TG 8.8

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Abstract

Innovative structures can be designed with flowable concrete. A homogenous fibre distribution has to be assured by adequate mix design, whereas the fibre orientation depends on the flow and casting conditions, fibre length and rheological properties. Important work has been carried out during the past years on test methods and methods for non-destructive testing highlighting the necessity for on-site assessment of material behaviour of fibre concrete. The translation of results of small scale specimens tested in bending or in uniaxial tension is not necessarily straightforward and easy to execute considering a larger number of affecting parameters in the case of flowable concrete.

This paper reviews the progress in understanding of how test results of small scale specimens relate to the structural behaviour of flowable fibre reinforced concrete. Results of recent studies reported in literature and carried out by members of fib Task Group 8.8 are considered.

Keywords

Flowable concrete, fibre, fibre orientation, test method, structural application

1 Introduction

Practicable and reliable test methods are required for fibre reinforced concrete (FRC), which also characterize the behaviour of FRC as a function of fibre orientation. Especially, for quality control during production such test methods are lacking or have important drawbacks. Recently, tests on cubes were proposed (destructive and non-destructive) that allow for the qualification in three different directions (i.e. Multidirectional Double-Punch Test (Blanco Álvarez, 2013) and the Double Edge Wedge-Spitting Test (Di Prisco, 2013)) taking into account the effect of both the distribution and the orientation of fibres. Herein, mainly steel fibres were considered and tested. Bending tests (3- or 4-point) are the most common test methods for FRC; an example is the three-point bending test according to EN 14561 (2005). The translation of experimental results of small test specimens to larger structures (Figure 1) has to be executed with care. The focus should be on the prescription concerning manufacturing and representativeness of the obtained orientation with respect to the intended application.

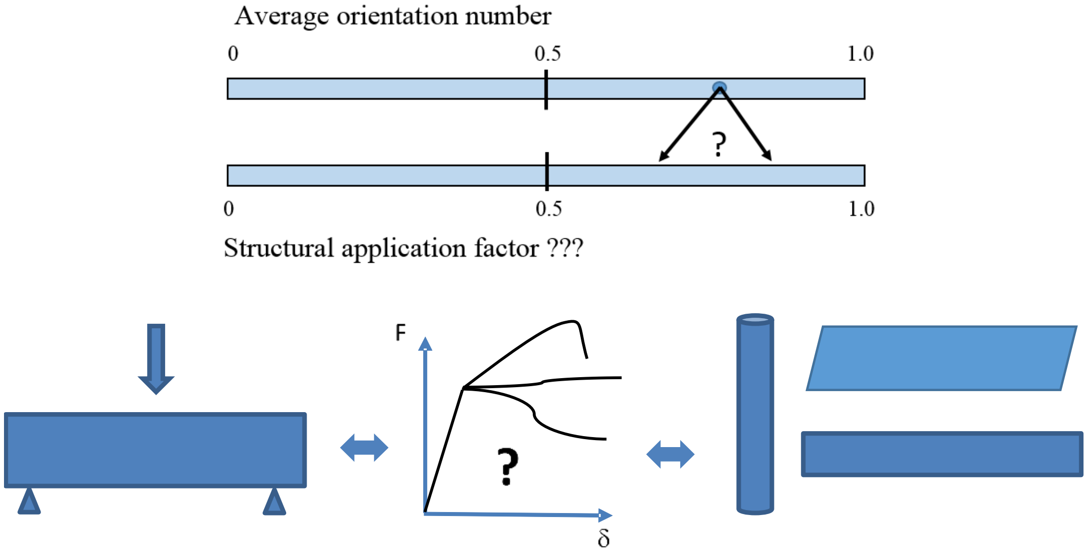


Figure 1: Translation of results of test specimens to the performance of full-scale structures

A homogenous fibre distribution (within reasonable boundaries) is a necessity for adequate design assumptions. For the translation of results obtained with small test specimens (i.e. prisms) to a structural performance several parameters have to be considered. A more favourable orientation of fibres in test specimens can result in an overestimation of the structural performance, whereas a large scatter and an orientation less favourable compared to a structure can result in an underestimation. Bartoli (2014) simulated the flexural performance of self-compacting fibre reinforced concrete (SCFRC) with single fibre pull-out behaviour as an input taking into account the distribution of fibre orientation in the cross-section. In order to demonstrate the effect of differences in fibre distribution and orientation Figure 2a shows the effect of the fibre dosage (60±20 kg/m^3) on the flexural behaviour and Figure 2b indicates the effect of a change in the average fibre orientation by ± 0.1.

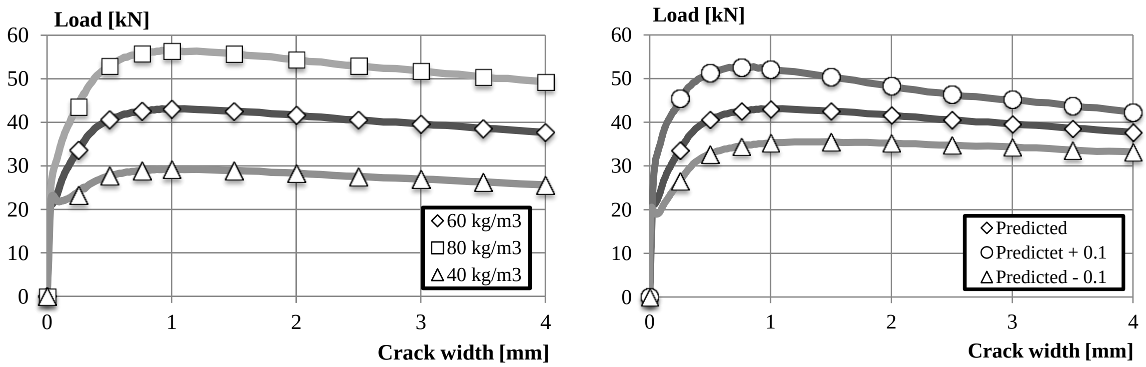


Figure 2: Analytical study on the influence of (a: left) the fibre dosage and (b: right) the average fibre orientation on the flexural performance of SCFRC, L_f=60 mm, L_f/d_f=80 (Bartoli, 2014)

2 Material parameters

Single fibre pull-out: Basic information concerning the behaviour of FRC is the pull-out behaviour of single fibres from the matrix. Markovic (2006) reviewed literature related to the pull-out force and showed that the difference can be significant for different orientation angles. The highest load for steel fibres usually is not obtained with perpendicular oriented fibres but with some inclination, which also depends on the geometry of the fibres. With angles higher than 30º the force can show a pronounced drop, which can be traced back to fibre rupture or failure of concrete surrounding the fibre (spalling of a concrete cone).

Fibre rotation: With a sufficiently low yield stress fibres start to rotate during the flow/movement of concrete and as a consequence the fibre orientation deviates from the state of randomness. The yield stress of concrete determines whether concrete flows or remains in a slope where is was cast; compaction energy has a pronounced effect on the yield stress. How concrete is compacted during casting (i.e. with a table vibrator or afterwards with a poker vibrator) determines the flow distance and related orientation of the fibres.

Neighbouring fibres: Concerning the fresh and the hardened state, it has been recognized that a high flowability has benefits for the performance of FRC, since the fibre distance in the matrix is sufficiently large in order to prevent significant interaction during the flow and consequently, fibres can be effectively pulled out. Neighbouring fibres can decrease the efficiency of a fibre compared to the single fibre pull-out test (Wijffels, 2013). With well-designed FRC fibres can exploit their full pull-out potential. Coarse aggregates occupy a relative large volume within which no fibres are present. A finer concrete contains relatively more fine aggregate particles and the volume occupied by the aggregates is smaller. As a result, fibres are better distributed compared to concrete that contains (more) coarse grains. Sato et al. (2000) carried out deformation-controlled tests in compression and uni-axial tension (Fig. 3). Based on a reference concrete without fibres, the effect of the type (straight and hooked-end), the dosage and combinations of steel fibres was studied. Uni-axial tensile strengths up to 30 MPa were obtained. Figure 3a shows the maximum strength obtained in the compression tests. In uni-axial tension (Fig. 3b), the results of combinations of fibres (white dots) followed a linear relationship with the fibre factor. However, short fibres only mixtures at higher dosages deviated from the linear trend of mixtures of fibres reflecting a decreased efficiency caused by very high fibre numbers. Because of size differences it was possible to add relative higher fibre dosages for fibre combinations.

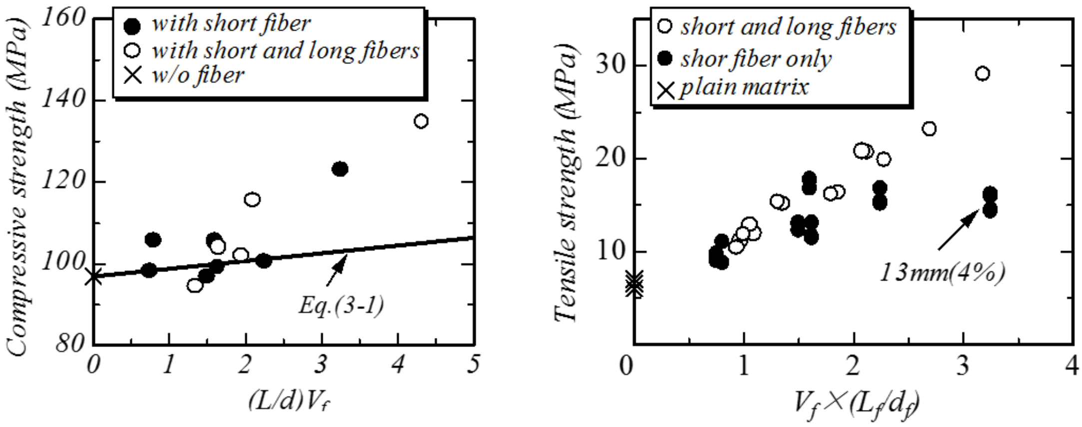


Figure 3: Comparing the fibre factor of steel fibres with: a) compressive strength and b) uni–axial tensile strength (Sato et al., 2000)

3 Production of test specimens

Geometry of test specimen: The post-cracking scatter of FRC with steel fibres in bending was studied by Parmentier et al. (2008). They concluded that the scatter was not only the result of the heterogeneity of the material (fibre dosage being the leading parameter) but it was also influenced by the specimen size and chosen test method. In their publication four test methods were considered. These test methods were: T1) 3-point bending test (EN 14651), T2) 4-point bending test (NBN B15-238), T3) Round panels (ASTM C1550-05) and T4) Square panels (EFNARC). Tests T1 and T3 were selected for the second test phase. The compressive strength of the tested concretes was 47 and 85 MPa. Dependent on the compressive strength either normal or high strength steel fibres were added. Seven fibre types (five steel and two synthetic fibre types) were tested in a second test phase with the selected two test methods T1 and T3. The fibre dosages were 30 kg/m^3 for steel and 4.5 kg/m^3 for synthetic fibres. The lowest scatter (less than 10%) was obtained with the round panel specimens (T3); the highest scatter (about 24%) was found with 3-point bending tests (T1). Round panels can redistribute stress after cracking, which is not possible for prisms. The coefficient of variation also depended on the fibre type; a relatively lower scatter was found for macro-synthetic fibres. The influence of the fibre dosage on the scatter was not clear. The variation of flexural results also depends on the width of a specimen; in a wider specimen the wall-effect is less pronounced and the contribution of the fibres is approaching an average performance (Kooiman, 2000).

Flow in test specimens: Martinie & Roussel (2011) describe two processes related to fibre orientation, which are the flow along boundaries (i.e. the wall of a formwork) and free-flow, in which fibres reach a relative stable position parallel to the casting front. In test specimens, the flow of concrete along walls is more relevant compared to the effect of free-flow on fibre orientation. Martinie & Roussel (2010) showed with flow simulations that the walls of a L-Box orient fibres more in the case of a flowable concrete compared to vibrated concrete, VC (Figure 4). By decreasing the yield value of VC during casting with compaction energy or by increasing the drop height of the concrete the difference becomes smaller.

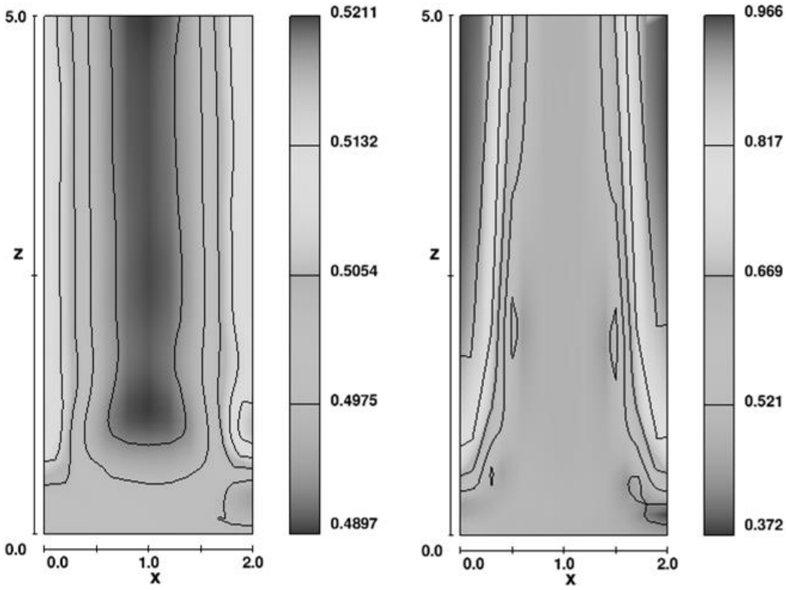
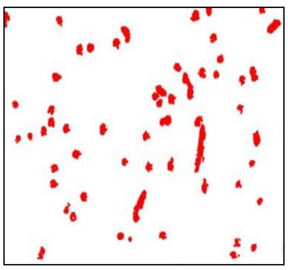


Figure 4: Orientation factor relative to the flow direction z; yield stress of concrete, left: 800 Pa, right: 50 Pa (Martinie & Roussel, 2010)

In Grünewald (2004), the average orientation number was determined by image analysis for different mixtures (Fig. 5), containing different fibre types: the average fibre orientation increased at increasing fibre length. Hereby, the flexural performance of the specimens relatively improved with longer fibres (see also Fig. 2b). The length of fibres relative to the specimen width and height determine the influence area of the walls.

$$\eta_\varphi = \frac{1}{N_{sf}} \cdot \sum_{1}^{N_{sf}} \cos\varphi$$



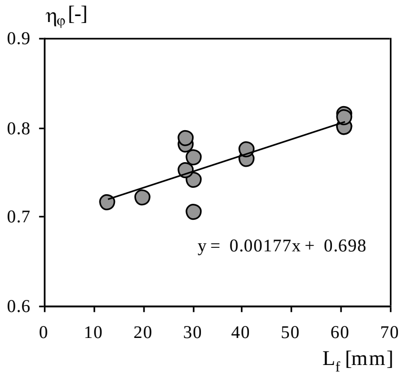


Figure 5: Calculation of the average orientation number, example of an image of a cross-section and relation between fibre length and average orientation number for SCFRC (Grünewald, 2004)

Relative to the bulk, fibres have a lower number of probable positions in a space around their centre of gravity in the vicinity of walls. The same holds true for more aligned fibres. Figure 6a illustrates possible locations of a fibre in a spherical space. Laranjeira (2010) studied the distribution of fibre orientation and observed that their distribution can be described with good accuracy with a Gaussian distribution around the average fibre orientation. Higher orientation numbers have as a consequence a more narrow bandwidth (Figure 6b).

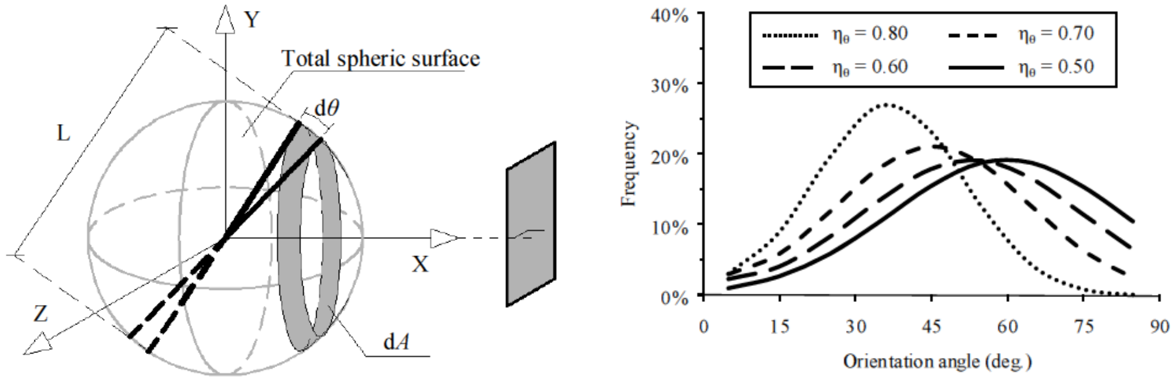


Figure 6: Possible orientation of a fibre in a spherical space (left) and dependency of the distribution of fibre orientation on the average fibre orientation (right) (Laranjeira, 2010)

Fibres usually are the longest components of concrete with common lengths of up to 60 mm. During the filling of a test specimen like a prism with a height of 150 mm, the concrete layer added (often with a shovel) is thinner than the length of the fibres. Fibres penetrate the previously cast layer, and hereby locally increase the fibre dosage, which can cause fibres to cluster. Two different casting methods were applied to fill self-compacting fibre reinforced concrete in prisms (Grünewald & Walraven, 2002); filling concrete containing 60 mm steel fibres with a bucket resulted in relatively higher fibre concentrations at the location where SCFRC entered the mould. Ferrara and Cresmonesi (2013) studied the use of a funnel as a tool to standardize the flow through prisms. The concrete had a slump flow of 680 mm after mixing; the fibre length of the hooked-end steel fibres was 35 mm (fibre dosage: 50 kg/m^3; maximum aggregate size: 8 mm). Thirteen beams (150x150x600 mm^3) were cast (nine from the centre and four from the end of the mould). Three-point bending tests were executed on notched specimens according to EN 14651 (2005). Higher bending stresses were observed for specimens filled from the centre of the mould (Fig. 7a). The number of fibres in the centre (1.45 fibres/cm^2 cast in the centre compared to 1.12 fibres/cm^2 cast at the end of the mould) indicates that some separation occurred at the point of casting where higher shear rates and stresses are present. Figure 7b compares the fibre orientation factor α with the maximum stress σ_N of the flexural tests.

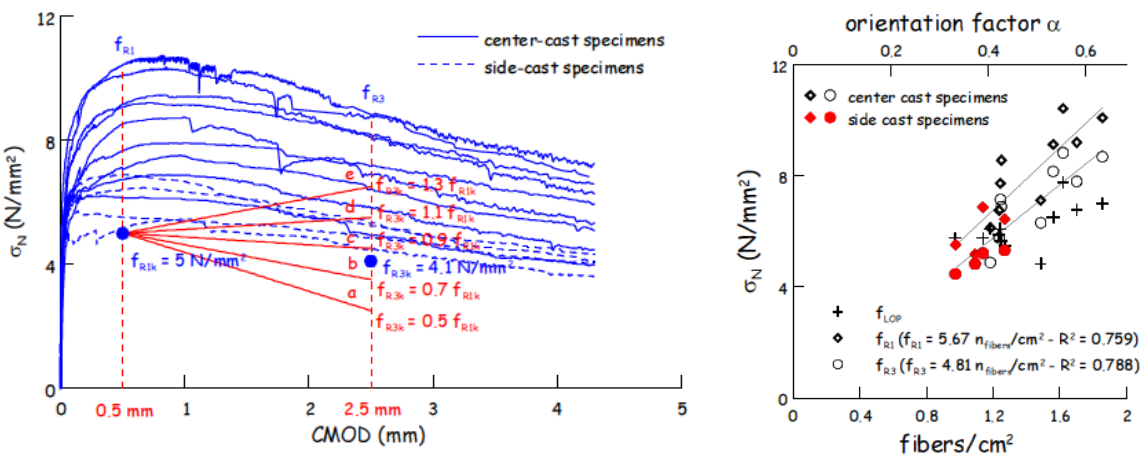


Figure 7: Three-point bending tests a) nominal stress - CMOD curves and material classification and b) bending stresses versus specific number of fibres and fibre orientation

4 From test specimen to structural application

Thin panels: Taking bending results as a basis for structural design the geometry of the structural element, rheological characteristics and casting conditions also have to be considered. Thin panels are a promising application for FRC. Bartoli (2014) produced panels (L/W/H: 800/500/60 mm) by applying different casting methods (span in bending test: 650 mm). Figure 8 shows two casting methods to produce panels. Plastic guides were positioned in Panel 1 to promote fibre orientation, whereas Panel 2 was cast with free-flow casting. The panels were cut in strokes having a width of 100 mm with which the flexural performance (three-point bending test with notch) was determined.

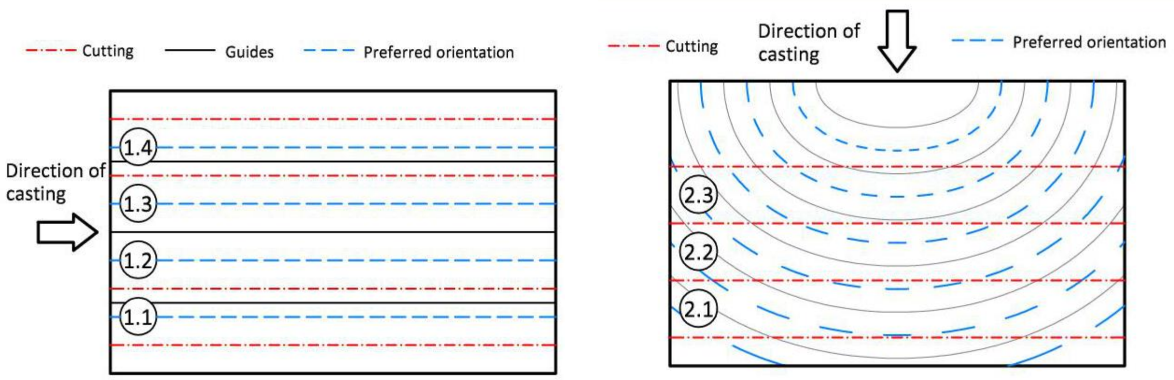


Figure 8: Casting conditions and cutting lines for panels produced a) with plastic guides and b) with free-flow condition

Figure 9 compares the results of the flexural tests on strokes cut from Panels 1 and 2. Due to the fast orientation of the fibres parallel to the concrete flow front and along the guides, in both cases similar results were obtained. The strokes produced with plastic guides originally positioned inside a specimen (Fig. 8a, Strokes 1.1 and 1.4) had a relative higher orientation number compared to the other strokes of the same panel. In an extended study the effect of the flow on the fibre orientation was studied and related to the flexural behaviour of prisms cut from thin panels (Ferrara et al., 2011).

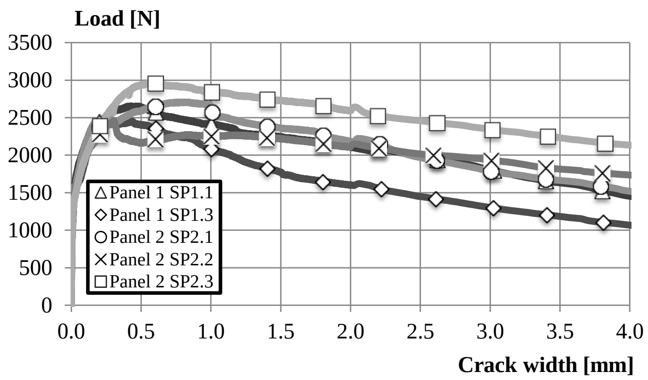


Figure 9: Results of flexural tests with specimens cut from panels cast with plastic guides (Panel 1) and with free-flow condition (Panel 2)

Prefabricated slabs: Blanco Álvarez (2013) and Pujadas Álvarez (2013) tested slabs with steel or plastic fibres being the only reinforcement. Three geometries were considered: a square slab (3x3x0.2 m^3) and two slabs with a shorter side (3x2x0.2 m^3 and 3x1x0.2 m^3). Concrete was cast in the middle and it was distributed with slight external vibration of the mould. The slabs were tested under a centre point load. With the slabs also prisms were cast, which were tested in bending. From the bending tests characteristic values were determined by inverse analysis to derive the tensile behaviour. The constitutive behaviour was then used as an input for finite element calculations. As a result, a significant overestimation of the capacity of all slabs was obtained; the difference decreased at increasing width of the slabs. Figure 10 compares FEM-simulations and experimental results for 3x1m^2 (left) and 3x3 m^2 (right) slabs.

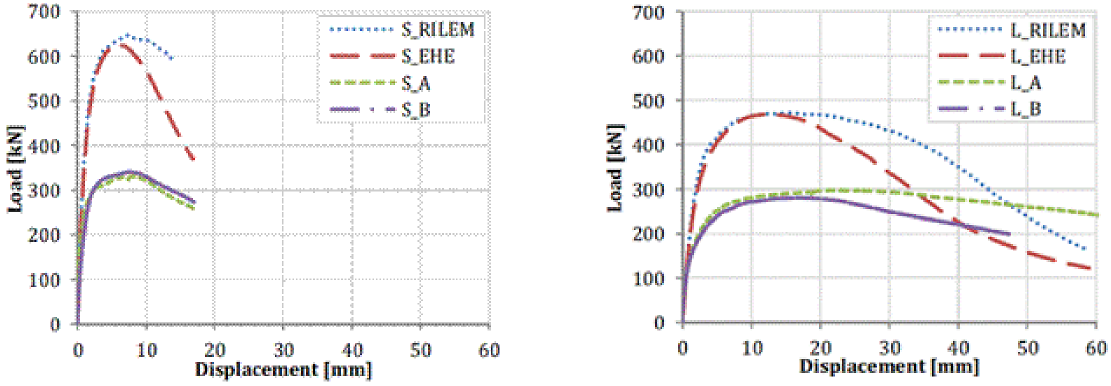


Figure 10: Comparison of experimental results of slabs compared with simulations (tensile behaviour according to RILEM- or Spanish EHE-codes) for a) the smallest slab (surface: 3x1m^2) and b) the largest slab (surface: 3x3 m^2) (Blanco Álvarez, 2013)

The differences between simulations and experimental results were explained by differences in specimen geometry and structural size favouring the fibre orientation in small test specimens. The performance of the larger slabs was relatively better compared to shorter ones, since the fibres in a free-flow situation tend to align themselves perpendicular to the flow direction which was better realized with a width of 3 m compared to 1 or 2 m. With the inductive method an indication of the fibre orientation was obtained (Fig. 11). Blanco Álvarez (2013) divided the slabs in three zones of characteristic fibre orientation (casting area, wall and intermediate area) and hereby explained the differences in load-bearing capacity of the slabs. Size factors were proposed to transfer results of small test prisms to the performance of large slabs.

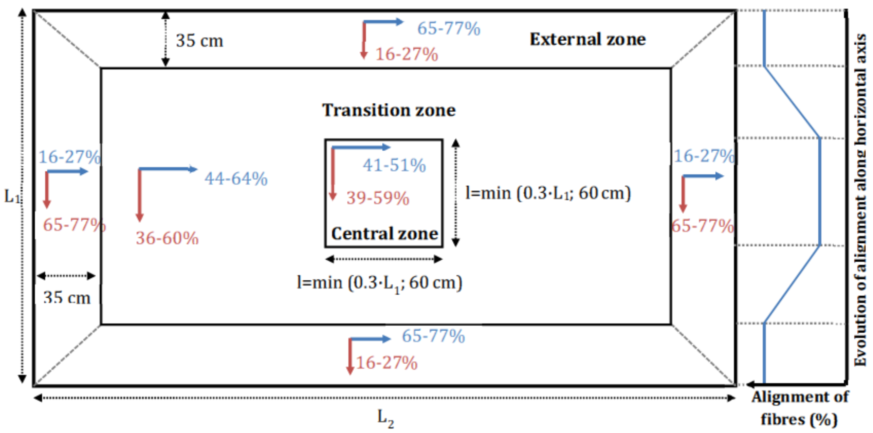


Figure 11: Division of a slab in areas dependent on the fibre orientation (Blanco Álvarez, 2013)

Beams and slabs: At NTNU Trondheim beams and slabs were tested containing reinforcement as well as hooked-end steel fibres (Nedrelid&Kanstad, 2013). The tested beams had the dimensions of 4000/200/300 mm (L/W/H) and a span of 3000 mm; two beams each were tested with fibre dosages of 1 or 2 Vol.-% (length: 60 mm, aspect ratio: 65). The beams were reinforced with a 20 mm rebar over the length of the beam. Bending tests according to EN 14651 (2005) were performed on small test specimens (containing no rebars). The residual flexural strength of the prisms was taken into account for the recalculation of the large beams. A good approximation of the flexural behaviour was obtained with 63 and 55% of the residual strength for 1 and 2 Vol.-% steel fibres, respectively. This result means that taking into account the residual strength obtained with small scale specimens overestimated the load-bearing capacity. Two simply-supported slabs were also tested (fibre dosage: 1 Vol.-%, placement of two 8 mm rebars). The dimensions of the slabs were 3000/900/150 mm (L/W/H) with a span of 900 mm. The slabs were equally loaded at both sides of the slab. Like for the beams the flexural behaviour was overestimated taking into account the residual strength of small test specimens in bending (a good fit was obtained with 67% of the residual strength).

K-factor concept: In MC2010 (fib, 2012), the K-factor concept was implemented, which is also included in the French UHPFRC-recommendation (AFGC, 2013) and which takes into account different influence parameters (concerning production and workability) and allows to transfer results of small scale specimens to the behaviour of structures made with UHPFRC. The K-factor validates design assumptions as a result of tests on parts of full-scale test elements. Simon et al. (2013) discusses the robustness and reliability of the K-factor concept with case-studies as a reference. The French UHPFRC-recommendation proposes as a first design approximation 1.75 for local effects and 1.25 for global effects. In several cases, K-factors lower than 1 were found, which is considered the minimum design value. In such cases, the performance of a part of a full-scale element was better than the experimental results of laboratory specimens. In case of the Pont Du Diable-footbridge the highest obtained local K-factor was 2.12. Such factors still have to be determined for specific applications and validated for FRC-types other than UHPFRC. Ferrara et al. (2012) found a linear relation between the residual strength and fibre orientation, which allows predicting the structural behaviour based on the actual fibre orientation in a structure.

5 Conclusions

Significant progress has been made during the past years related to the development of test methods (destructive and non-destructive) and the understanding of what affects the performance of small test specimens and structures. Further development and validation are required to link fibre orientation, the test response of small test specimens and structural response as a basis for reliable design guidelines.

6 References

AFGC:2013, *UHPFRC*, Recommendations, AFGC Groupe de travail BFUP.

Bartoli, L. (2014), *Self-Compacting Fibre Reinforced Concrete - Tailoring fibres' orientation: experiments and modelling*, Master-thesis, Delft University of Technology.

Blanco Álvarez, A. (2013), *Characterization and modelling of SFRC elements*, Ph.D. thesis, Universitat Politècnica de Catalunya, Barcelona.

Di Prisco, M.; Ferrara, L.; Lamperti, M. (2013), *Double edge wedge splitting (DEWS): an indirect tension test to identify post-behaviour of fibre reinforced cementitious composites*, Materials and Structures, DOI 10.1617/s11527-013-0028-2.

EN 14651:2005, *Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)*.

Ferrara, L.; Cremonesi, M. (2013), *Effects of casting process on toughness properties of Fiber Reinforced-Self Compacting Concrete as from EN 14651*, Proceedings of 7th RILEM Int. Conference on SCC, Roussel, N.; Bessaies-Bey, H. (Eds.), Paris, RILEM Publications S.A.R.L., Bagneux, ISBN: 978-2-35158-137-7, CD.

Ferrara, L.; Caverzan, A.; Muhaxheri, M.; Di Prisco, M. (2012), *Identification of tensile behaviour of SFR-SCC: Direct VS. indirect tests*, Proceedings BEFIB 2012 – Fibre reinforced concrete: challenges en opportunities, Barros, J. et al. (Eds.), ISBN: 978-2-35158-132-2, pp. 83-84&CD.

Ferrara, L.; Ozyurt, N.; di Prisco, M. (2001), *High mechanical performance of fiber reinforced cementitious composites: the role of "casting-flow" induced fiber orientation*, Materials and Structures, Vol. 44, n° 1, pp. 109-128.

fib bulletin 65 (2012), *Model Code 2010, Final draft, Volume 1*, fédération internationale du béton (fib), Lausanne, Switzerland, ISBN: 978-2-88394-105-2.

Grünewald, S. (2004), *Performance-based design of self-compacting fibre reinforced concrete*, Ph.D. thesis, Delft University of Technology, Department of Structural and Building Engineering, ISBN: 9040724873.

Grünewald, S.; Walraven, J.C. (2002), *Sensitivity of the bending behaviour of self-compacting fibre reinforced concrete to the method of casting*, 5th International Symposium on Cement and Concrete, Conference in Shanghai, China, pp. 1160-1165.

Kooiman, A. (2000), *Modelling Steel Fibre Reinforced Concrete for Structural Design*, Ph.D. thesis, Department of Structural Engineering, Delft University of Technology.

Laranjeira, F. (2010), *Design-oriented constitutive model for steel fiber reinforced concrete*, Ph.D. thesis, Universitat Politècnica de Catalunya, Barcelona.

Markovic, I. (2006), *High-Performance Hybrid-Fibre Concrete: Development and Utilisation*, Ph.D. thesis, Delft University of Technology.

Martinie, L.; Roussel, N. (2010), *Fiber-Reinforced Cementitious Materials: From Intrinsic Properties to Fiber Alignment*, In: Design, Production and Placement of Self-Consolidating Concrete, Khayat, K.; Feys, D. (Eds.), Rilem Bookseries 1, ISBN: 978-90-481-9663-0, pp. 407-415.

Martinie, L.; Roussel, N. (2011), *Simple tools for fiber orientation prediction in industrial practice*, Cement and Concrete Research, 41, pp. 993-1000.

Nedrelid, H.; Kanstad, T. (2013), *Structural fibre-reinforced concrete - Design approaches and experimental results*, Interim report COIN-project, NTNU Trondheim.

Parmentier, B.; Vandewalle, L.; Rickstal, F. van (2008), *Evaluation of the scatter of the postpeak behaviour of fibre reinforced concrete in bending: A step towards reliability*, in BEFIB 2008, 7th RILEM Symposium on FRC, Gettu (Ed.), RILEM publications S.A.R.L., Bagneux, ISBN: 978-2-35158-064-6, pp. 133-143.

Pujadas Álvarez, P. (2013), *Caracterización y diseño del hormigón reforzado con fibras plásticas*, Ph.D. thesis, Universitat Politècnica de Catalunya, Barcelona (in Spanish).

Sato, Y.; Mier, J.G.M. van; Walraven, J.C. (2000), *Mechanical characteristics of multi-modal fiber reinforced cement based composites*, Befib 2000, Lyon, Rossi, P. & Chanvillard, G. (Eds.), Cachan Cedex, ISBN: 2-912143-18-7, pp. 791-800.

Simon, A. ; Corvez, D. ; Marchand, P. (2013), *Feedback of a ten years assessment of fibre distribution using K factor concept*, Int. Symposium on UHPFRC, Designing and Building with UHPFRC: from innovation to large-scale realizations, RILEM Publications S.A.R.L., Bagneux, ISBN: 978-2-35158-130-8, pp. 669-678.

Wijffels, M.J.H. (2013), *Magnetically orienting steel fibres in self-compacting concrete*, Master-thesis, TU Eindhoven.