FIBRE ORIENTATION IN SFRC SLABS

BLANCO Ana [1], PUJADAS Pablo [2], DE LA FUENTE Albert [3],
CAVALARO Sergio [4], AGUADO Antonio [5]

Abstract

The orientation factor introduced in the Model Code 2010 represents a paramount step forward in the design of FRC structures, however the cases in which it should be used to penalize or to improve the mechanical performance of the material are vaguely defined. In order to provide a more accurate definition of the effect of fibre orientation in the design codes and to work towards an optimal design of SFRC structures, deeper insight regarding the fibre orientation in certain types of structures is required. This paper presents a study on the orientation of steel fibres in full-scale slabs with different dimensions, which was assessed by drilling cores from the slabs and testing them by means of a non-destructive inductive method. The results reveal that the fibres tend to rotate and align perpendicularly to the extensional flow. Based on the results, a fibre orientation pattern for a random slab is proposed. This pattern suggests the division of the slab in three main zones and a certain orientation is attributed to each one.

Keywords: SFRC, fibre, orientation, pattern, slabs, inductive method

1. Introduction

In the field of fibre reinforcement technology, fibre orientation has become a fundamental property given its influence in the response of fibre reinforced concrete (FRC) structures. Research has provided evidence fibre orientation is governed by several factors such as the fresh-state properties of the concrete after mixing, the production process as well as the geometry of the formwork [1, 2]. Hence, preferential orientations of the fibres may occur as a results of the different stages involved in the manufacturing and casting procedure. Despite the significant role that fibre orientation played in the structural response of FRC, it was not integrated in the design considerations until the Model Code 2010 [3] introduced an orientation factor, which affects the design serviceability and ultimate residual strengths when favourable or unfavourable fibre orientation effects are experimentally verified. At this point, several questions may be posed: How can be a favourable or an unfavourable

[1] BLANCO Ana, UPC, Jordi Girona 1-3 Building C1 Room 202 08034 Barcelona (Spain), ana.blanco@upc.edu

[2] PUJADAS Pablo, UPC, Jordi Girona 1-3 Building C1 Room 202 08034 Barcelona (Spain), pablo.pujads@upc.edu

[3] DE LA FUENTE Albert, UPC, Jordi Girona 1-3 Building C1 Room 202 08034 Barcelona (Spain), albert.de.la.fuente@upc.edu

[4] CAVALARO Sergio, UPC, Jordi Girona 1-3 Building B1 Room 106 08034 Barcelona (Spain), sergio.pialarissi@upc.edu

[5] AGUADO Antonio, UPC, Jordi Girona 1-3 Building C1 Room 202 08034 Barcelona (Spain), ana.aguado@upc.edu

fibre orientation quantified? It is known, that if controlled, fibre orientation may enhance the tensile behaviour [4]. Could a favourable preferential orientation be induced and assessed in terms of the orientation factor? Which parameters should affect the orientation factor (geometry of the structure, casting procedure, etc.)?

The orientation factor proposed by the Model Code 2010 is a great step forward in the design of FRC structures, nevertheless some aspects of its definition and quantification are vaguely defined. This new philosophy of design, which includes fibre orientation, requires further research regarding the fibre orientation in different applications of FRC.

In this regard, an application in which a preferential orientation caused by the geometry results advantageous in terms of mechanical behaviour is slabs since the fibres tend to align in the perpendicular plane to the filling direction, which in turn is perpendicular to the failure planes that develop in this type of structures. This study focuses in the assessment of fibre orientation in SFRC slabs with different dimensions with the aim to gain deeper insight into the phenomenon of orientation in this typology of structure.

2. Experimental program

2.1 Specimens

A total of 6 slabs with 3.0 m of length and 0.2 m of thickness and three different widths were produced. The notation for the slabs is small (S), medium (M) and large (L) depending on the width is 1.5 m, 2.0 m or 3.0 m, respectively. The letters A or B are appended at the end of the notation to indicate each one of the two slabs with the same dimension. The slabs were cast at the facilities of ESCOFET SA and then transported to the Laboratory of Structure Technology Luis Agulló at Universitat Politècnica de Catalunya (UPC) to be tested.

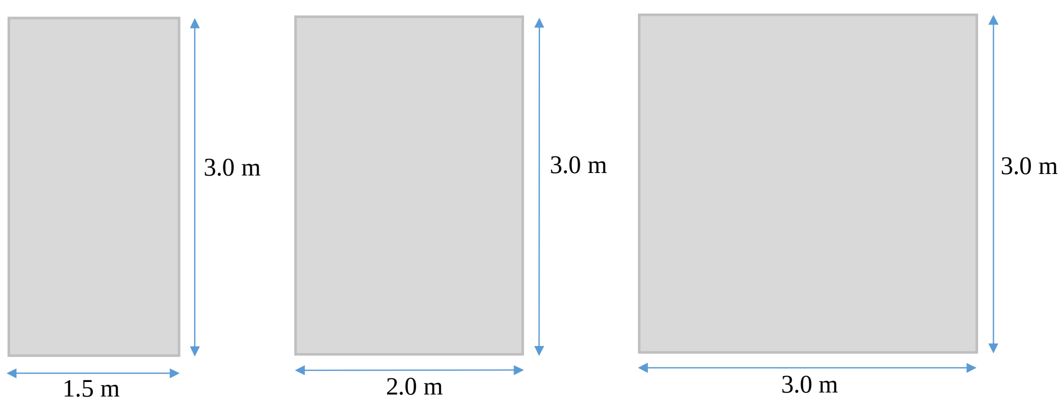


Fig. 1: Dimensions of the slabs: a) small (S), b) medium (M) and large (L).

2.2 Materials and concrete mix

A 750 litres vertical axis mixer was used to produce the concrete. The mixing process consisted in mixing the aggregates and the cement during one minute and afterwards adding the water. These components were mixed for another two minutes. Subsequently, the superplasticizer was added and finally the steel fibres were included. The steel fibres used were Dramix® RC80/50BN with a circular cross-section and hooked ends. These fibres are made of low carbon steel and are gathered into bundles by water-soluble glue. After that, the concrete was mixed for two additional minutes. The concrete mix was designed to obtain a fluid concrete with characteristics close to self-compactability. The details of the concrete mix are presented in Tab.1.

Tab.1: Concrete mix

Components	**Characteristics**	**Content [kg/m³]**
Gravel (6/15 mm)	Granite	520
Gravel (2.5/6 mm)	Granite	400
Sand (0/3 mm)	Granite	510
Cement	CEM I 52,5 R	350
Filler	Marble dust	300
Water	-	178
Superplasticizer	Adva® Flow 400	12
Fibres	Steel fibres	40

The casting procedure was the same for all slabs since the pouring method influences fibre orientation. Hence, the concrete was poured from the centre (see Fig.1) by means of a skip with straight outlet from a height of 50-60 cm over the surface of the formwork.

Fig. 2: Concrete pouring in the centre of the slab.

The concrete was vibrated during 15 to 20 seconds with a portable system attached to the walls of the formwork. This procedure aimed at ensuring a uniform distribution of the concrete in the mould. The slabs were removed from the moulds within 24 hours after casting and were moist cured under a plastic sheet during 20 days. Further details on the material properties may be found in [5].

2.3 Assessment of fibre orientation

The fibre orientation in the slabs was assessed by means of a non-destructive inductive method [6-7] in cubic specimens extracted from the slabs. This method was already applied to real scale structures to assess fibre content and fibre orientation [8]. In this case, between 12 and 18 cylindrical cores were drilled from each slab. The position of the cores in the slabs was defined trying to cover the largest surface possible (see Fig.9a) and its location and orientation with regards to the slab was properly marked.

The cylindrical cores presented a height of 200 mm and a diameter of 225 mm and were cut into 150 mm cubic samples that are required for the test. The cutting procedure started with the lateral edges of the cylinders to obtain a 150 x 150 x 200 mm prisms (see Fig. 9b). Finally, the top and bottom 25 mm were cut to obtain the final specimen for the test (see Fig.9c). Notice that the sides of the resulting cubes were parallel to the sides of the slabs.

Fig. 3: a) Detail of the slab after drilling, b) cut of cylindrical cores and c) cubic specimens.

The non-destructive inductive method selected for assessing fibre orientation is based on the ferromagnetic properties of the steel fibres. Steel fibres are able to alter the magnetic field around them. By measuring these alterations in the three main axes of the cubic specimen, information regarding the orientation of the fibres along the three axes in terms of percentage of the total amount of fibres is obtained. This testing method was developed at UPC as a result of the collaboration between the Departments of Electronic Engineering and Construction Engineering.

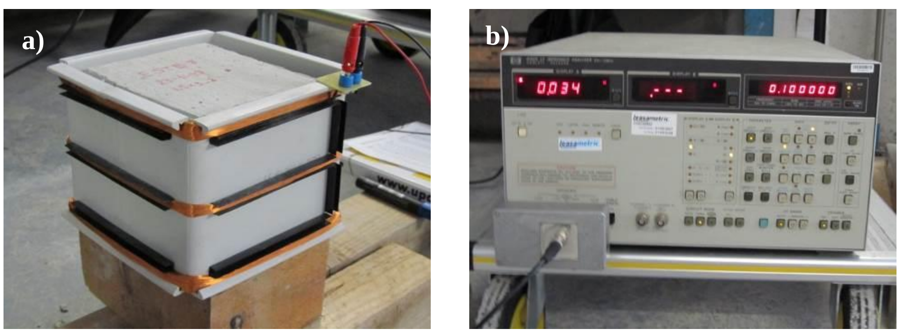


Fig. 4: Equipment of the inductive method: a) coil and b) impedance analyser.

3. Results of fibre orientation

The fibre orientation assessed in the specimens is represented in a map with the location of each specimen, thus providing a general view of the orientation of the fibres in all the surface of the slab (see Fig.5). The orientation is expressed in terms of percentage of fibres aligned along either X or Y axes and are represented with different colours to facilitate the comprehension (blue along X axis and red along Y axis).

The percentages presented in Fig.5 indicate that the fibres align in the horizontal plane. This preferential orientation was expected given the dimensions of the element and the casting procedure used. Moreover, a local phenomenon of preferential orientation is detected in the specimens located near the sides of the slab. This phenomenon is characterized by the alignment of the fibres in the parallel direction to the boundaries (see specimens located near the sides of the slab in Fig.14). Such outcome is the result of the flow and the wall-effect of the formwork.

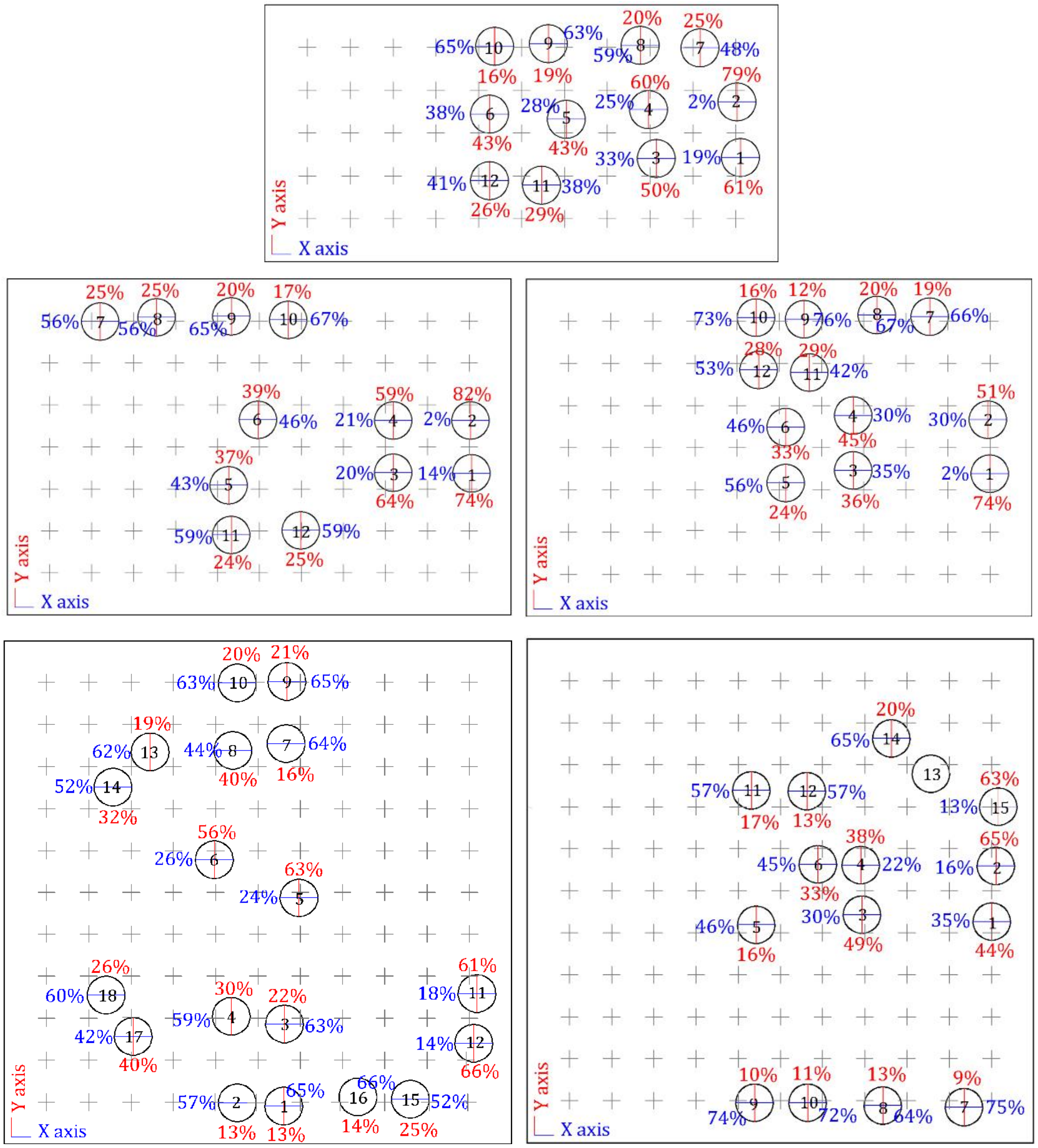
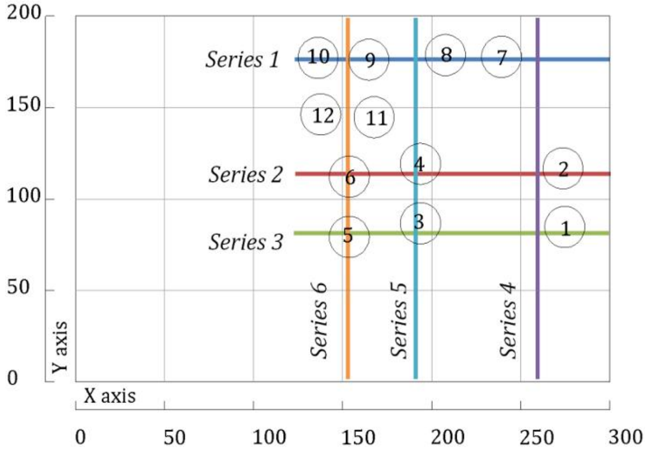


Fig. 5: Fibre orientation in specimens of: a) S_B, b) M_A, c) M_B, d) L_A and e) L_B.

The results reveal that the fibre orientation changes as the distance from the casting point increases. In fact, as a general trend the specimens located near the centre of the slab present similar orientations in both axes. Contrary to those specimens, the ones located near the edges present a significant difference in the orientation along X and Y axes due to the wall-effect caused by the formwork.

This phenomenon may be easily visualized if the specimens are distributed into series along X and Y axes as indicated in Fig.6. As an example, the specimens of slab M_B are subsequently analysed. The results of Fig.7 reveal that the behaviour of series 2 and 3 (along X axis) and series 5 and 6 (along Y axis) agree with the described previously, presenting similar fibre alignments in both directions at the centre of the slab. Series 1 and 4 do not follow the same tendency since they are very close to the edges and thus influenced by the wall-effect.



Series	Specimens
1	7, 8, 9, 10
2	2, 4, 6
3	1, 3, 5
4	1, 2, 7
5	3, 4, 8
6	5, 6, 9, 11

Fig. 6: Distribution of specimens in slab M_B.

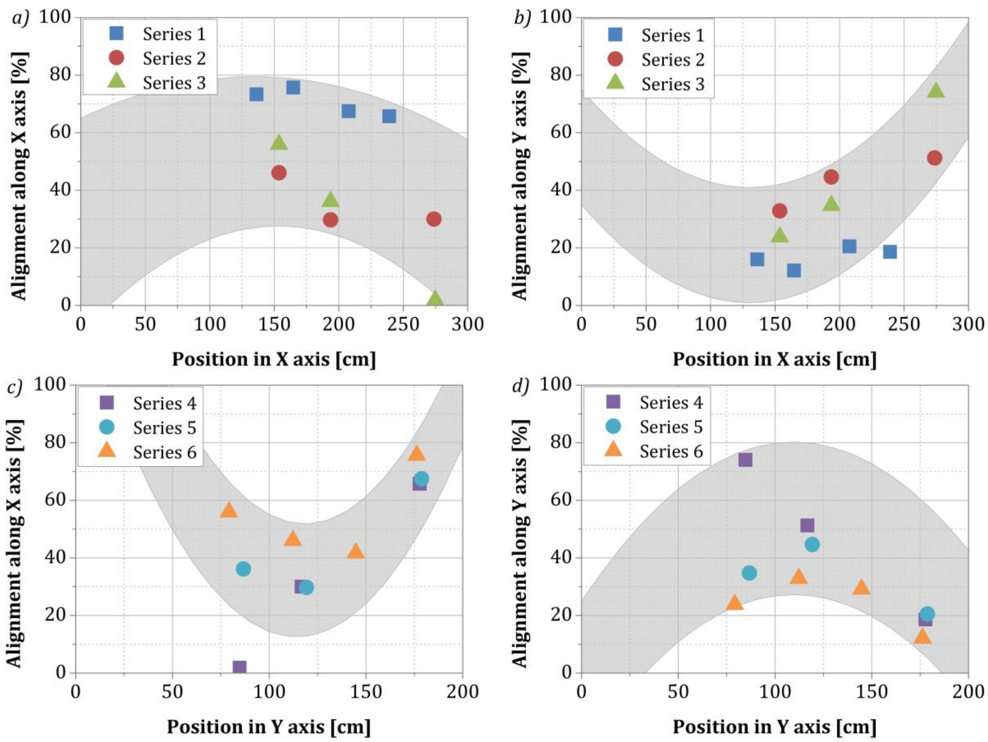


Fig. 7: Alignment along X-and Y-axes for series a) 1-3 and b) 4-6 in slab M_B.

The tendency observed in the results is governed by two phenomena: the wall-effect caused by the formwork and the flow of the concrete. According to the latter, the fibres are exposed to forces and the velocity profile exerted by the movement of concrete, which causes them to drift, rotate and align perpendicular to the direction of the flow. Hence, the fibres tend to change their orientation from the location they are poured, at the centre of the slab, as they advance towards the edges of the slab. This becomes more evident at increasing flow distance covered by the FRC. This orientation is in accordance with other experimental studies, in which the flow is governed by extensional stresses [1, 9, 10].

4. Orientation pattern

As a result of the orientation observed, an orientation pattern is proposed for a random slab. Three main zones of orientation may be defined: central zone, transition zone and external zone, as indicated in Fig.8. In the first zone, a similar alignment of fibres may be assumed in both axes, whereas in the external zone a preferential orientation parallel to the edges is observed. The transition zone represents a change between the other two. The characteristic orientation in each zone is indicated by a range of values, in which the lowest value is defined by the second quartile and the highest by the 95th percentile of the results of the specimens from all slabs located in the same zone.

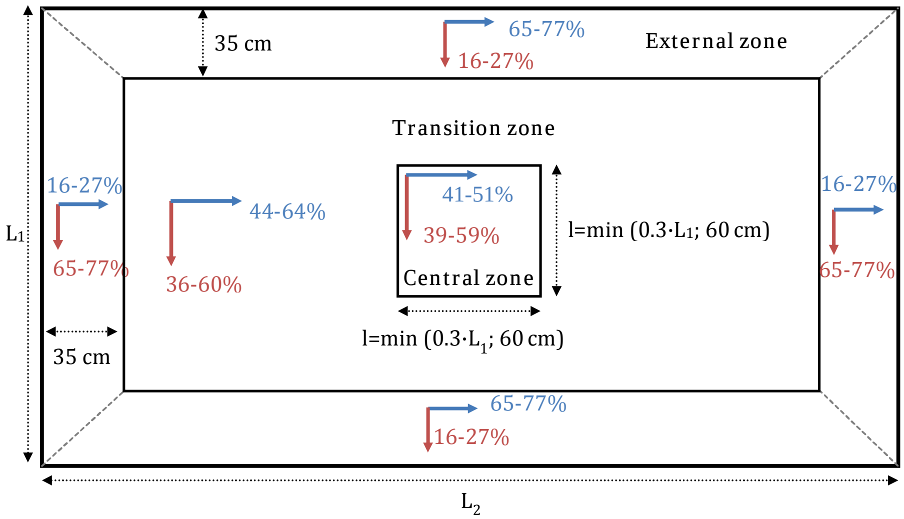


Fig. 8: Division of slabs in zones depending on fibre orientation.

The extension of the external zone is set by the average distances containing the cores from the edge. A double condition is defined for the central zone depending on the length L1 (where L1≤ L2), which takes into account that in a narrow slab the distance covered by the concrete flow is shorter in one direction (the minimum value between 0.3žL1 and 60 cm). This condition is necessary since, in such cases, the concrete flow would reach the edges in one direction much earlier than in the other direction, raising the level of the concrete and affecting the upcoming concrete flow. This creates a new border acting as a wall that would change the orientation of the fibres, thus reducing the extent of the central zone. This orientation pattern is based on the study performed on the slabs. Further research, including other geometries, could improve the annotation of the zones proposed.

5. Conclusions

The study conducted on the orientation of steel fibres in slabs reveals that in radial or extensional flows, the fibres tend to rotate and align perpendicular. Based on the geometries analysed, a pattern is proposed to identify the orientation of the fibres depending on their location in the slab. Three main zones are suggested: the central zone presents a similar percentage of fibres aligned along X- and Y-axes, whereas the external zone is characterized by a significant difference in the alignment of fibres along both axes due to the flow and the wall-effect. The transition zone marks a change between the others.

Acknowledgements

The authors of this document wish to show their gratitude for the economic support received through the Research Project BIA2010-17478: Construction processes by means of fibre reinforced concretes. The authors thank the company ESCOFET S.A. for their collaboration in the development of the experimental program. The first and second authors acknowledge the grant FI provided by the Comissionat per a Universitats del DIUE de la Generalitat de Catalunya i del Fons Social Europeu and the Grant FPI-UPC provided by the UPC, respectively. The first and second authors also acknowledge the support of the Col·legi d'Enginyers de Camins, Canals i Ports de Catalunya.

References

[1] Grünewald, S. *Performance-based design of self-compacting fibre reinforced concrete*. Doctoral Thesis, Delft University of Technology, Delft, 2004.

[2] Laranjeira, F. *Design-oriented constitutive model for steel fiber reinforced concrete*, Doctoral Thesis, Universitat Politècnica de Catalunya, Barcelona, 2010.

[3] fib. *Model Code 2010*, International Federation for Structural Concrete, Lausanne, 2010.

[4] Grünewald, S., Laranjeira, F., Walraven, J., Aguado, A., Molins, C. Improved tensile performance with fiber reinforced self-compacting concrete. In: Proceedings of the 6th International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC *6)*, Ann Arbor, Michigan, June 20-22 2011, Parra-Montesinos, Reinhardt, Naaman Eds.

[5] Blanco, A. *Characterization and modelling of SFRC elements*, Doctoral Thesis, Universitat Politècnica de Catalunya, Barcelona, 2013.

[6] Juan-García, P. Evaluación no destructiva de estructuras de obra civil mediante métodos electromagnéticos. Doctoral Thesis, Universitat Politècnica de Catalunya, Barcelona, 2011 (In Spanish).

[7] Torrents, J., Blanco, A., Pujadas, P., Aguado, A., Juan-García, P., Sánchez-Moragues, M. Inductive method for assessing the amount and orientation of steel fibers in concrete. *Materials and Structures*, 2012, 45(10):1-16.

[8] Orbe, A., Cuadrado, J., Losada, R., Rojí, E. Framework for the design and analysis of steel fibre reinforced self-compacting concrete structures. *Construction and Building Materials*, 2012, 35:676-86.

[9] Boulekbache, B., Hamrat, M., Chemrouk, M., Amziane, S. Flowability of fibre-reinforced concrete and its effect on the mechanical properties of the material. *Construction and Building Materials*, 2010, 24(9):1664-71.

[10] Barnett S, Lataste J-F, Parry T, Millard S, Soutsos M. Assessment of fibre orientation in ultra high performance fibre reinforced concrete and its effect on flexural strength. *Materials and Structures*, 2010, 43(7):1009-23.