INFLUENCE OF FIBRE AMOUNT ON SFRC PRE- AND POST-CRACK BEHAVIOUR

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ABSTRACT

Researchers agree that the number and orientation of the fibres largely influence the properties of steel fibre reinforced concrete (SFRC) member before and after cracking. There are proposed models in the literature, which can be used to predict the fibre number per cross-section assuming homogeneous fibre distribution. Thus, the expected number of fibres in every section can be calculated from the total fibre amount per volume. Nevertheless, other researches based on experimental data have shown that there is a difference between the theoretical and actual number of fibres, and it varies for different fibre volume fractions. In this paper experimental investigation of fibre distribution and orientation is represented. The location of cracks with respect to the fibre distribution in flexural elements is studied. It is shown by this research, that the theoretical prognosis of the fibre number per cross-section may largely overestimate the actual number of fibres in the fracture plane.

Key words: steel fibres, fibre density, fibre distribution, fibre orientation, cracks

INTRODUCTION

One of the most important factors, influencing behaviour of a structural element, is the distribution of reinforcement in the material. If SFRC is compared with conventionally reinforced concrete, the main difference is the uncertainty and unpredictability of the location and orientation of reinforcement in SFRC. Indeed, fibres are randomly distributed throughout the concrete and their spatial position can be influenced by numerous factors.

Experimental studies have shown that strong connection exists between the fibre distribution, workability and the mechanical properties of fibre reinforced concrete (Ferrara and Meda, 2006). It was observed for a large number of test series that the measured equivalent flexural tensile strength is proportional to the number of effective fibres crossing the crack (Dupont, 2003).

Deformation and strength properties of uncracked and cracked SFRC elements are affected by fibre distribution in terms of the three main aspects: 1) fibre amount bridging a fracture plane; 2) uniformity of the distribution of fibres all through the cross-section; 3) orientation of fibres corresponding to the longitudinal axis of the element. Although there are analytical methods for predicting the fibre number per cross-section of a structural element, most of them are based on assumptions of homogeneous fibre distribution, where no segregation of fibres is considered. Thus, the number of fibres in a particular section is proportional to the total number of fibres per unit of volume. Actually, many authors have studied the relationship between the content of fibres V_f and the number of fibres n_f counted on the fracture surface of the tested specimens. As it was expected, n_f increased with V_f, but the V_f –n_f relationship has large scatter since the fibre distribution depends on many factors such as the fibre geometric characteristics, concrete composition and cross section dimensions of the element (Barros et al., 2005; Barragán et al., 2003). Due to uneven fibre distribution the number of effective fibres along the length of a structure is also different.

Besides the fibre amount, the distribution of fibres throughout the particular cross-section is significant. The efficiency of fibres reduces, if they are not distributed evenly or they are concentrated in regions, where no tensile stress needs to be transferred. On the other hand, Stahli et al. (2008) observed that fibre segregation led to a much higher bending strength than expected due to fibre alignment only, at least as long as the segregated fibres are located along the tensile stressed part of the beam.

The effectiveness of fibres in the fracture plane is largely influenced by the orientation of the fibres. There is a correlation between the bending strength and fibre alignment: better fibre-alignment leads to a higher bending strength (Stahli et al., 2008). The analysis of the bond properties between the fibres and concrete shows that the maximum pull-out force has to be applied to the fibres with the inclination angle of 0 ... 20 (Robins et al., 2002). Furthermore, the fibres oriented almost parallel to the crack plane, have no direct contribution in stress bridging. The average orientation of fibres is commonly characterized through the so-called orientation number which varies from 0.0 to 1.0 referring to fibres parallel and orthogonal to the

analysed cross-section, respectively. Large orientation numbers not only provide improved properties, but also induce smaller scattering on the performance, which may be an aspect of superior importance for design purposes (Laranjeira et al., 2011).
The aim of this study is to investigate the influence of fibre distribution and orientation on the crack initiation in SFRC flexural elements and to evaluate the applicability of analytical methods for predicting number of fibres in fracture plane. Concrete beams with normal dosage of fibres, beforehand tested in four-point bending till failure, were sawn in multiple sections in three main directions, and fibres were manually counted on all surfaces. The obtained data are compared with the results calculated by an analytical method available in literature.

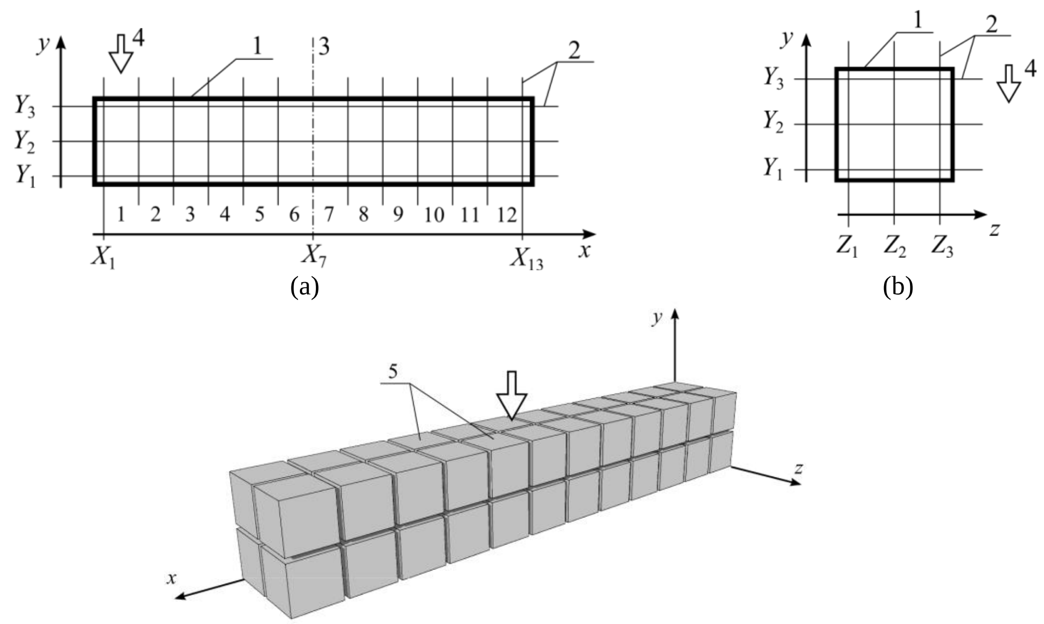
EXPERIMENTAL STUDY

Manufacturing of the specimens

The experimental investigations on fibre distribution and orientation were performed on SFRC beams with dimensions of 100×100×500 mm. Samples with different types and amount of fibres were manufactured, tested under four-point bending till failure and then sawn for counting the number of fibres on every "new" surface of prismatic specimens.
Fibres of three different shapes were used: 1) crimped, 2) hooked with round cross-section, and 3) crimped with flat cross-section. The samples with crimped round fibres were marked as group S1, samples with hooked fibres – as group S2, and samples with crimped flat fibres – as group S3. There were three specimens in every group, thus altogether 9 specimens were observed. The nominal fibre amount for groups S1 and S3 was 1% by volume (or approx. 80 kg/m^3) and 0.75% by volume (approx. 60 kg/m^3) for group S2. The length of the fibres of all types was 50 mm. Crimped-round and hooked fibres were of equal diameter of 0.75 mm, while crimped flat fibres were with a larger cross-sectional area thus less in number per kg.

Counting of fibres

Hardened samples, after testing under four-point bending, were sawn with a diamond circular saw and every specimen was marked according to its position in the specimen. For determining the fibre distribution the manual fibre counting method was used, which is applicable for specimens with normal fibre dosages up to 80 kg/m3 (Gettu, 2005). The number of cut fibres was registered for three main directions. The fibres crossing *X*-planes were considered as ones oriented in the longitudinal direction. The fibres counted on *Y*- and *Z*-planes are considered as ones aligned transversally to the main axis of the beams in vertical and horizontal directions respectively. The direction of concrete casting and compacting is considered as the vertical direction, which is represented by *Y*-planes. The cutting planes are shown in Figure 1.
Longitudinal planes were located in the middle and at a distance of 10 mm from each side of the beams. Transversal cuts were made with a distance of 40 mm starting at a distance of 10 mm from each end of the specimen. Thus, from each specimen 48 sample cubes with the length of the edge of 40 mm and area of a side of 16 cm2 were obtained.



(c)
Figure 1. Position of planes used for fibre distribution analysis,

Where: (a) longitudinal side view, (b) cross-section, (c) 3D view; 1 – sample beams, 2 – cutting planes, 3 – plane of symmetry, 4 – casting direction, 5 – cube specimens

For every beam there were 52 planes with the dimensions of 40×40 mm normal to the longitudinal axis. The planes parallel to the longitudinal axis were 72 in each direction. The total number of the observed planes was 196. The fibres in each plane were counted and the average was noted.

Results and analysis

It was observed that the distribution and orientation of the fibres in the manufactured specimens were influenced by two main factors, which are mentioned by other researchers as well. First, the fibre orientation is much influenced in the regions near the walls of the moulds, which is called the wall-effect. In the observed specimens the number of the cut fibres is notably smaller in the outer planes compared with the number in the middle planes. Second, the distribution and orientation of the fibres is affected by the technique used for concrete placing and compacting.

If fibre distribution along the length of the beam specimen is assessed, the difference between the average values of the fibre count in the longitudinal and transversal planes is insignificant. However, there are differences in the “shape” of the distributions. The comparison of the fibre density (number of fibres per 1 cm^2) for different directions along the length of the beams of group S1 is illustrated in Figure 2.

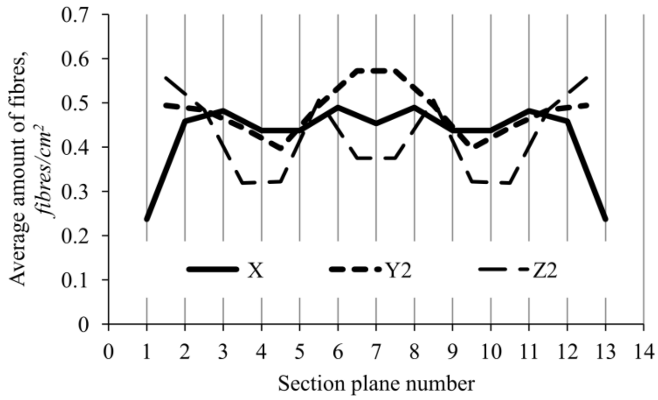


Figure 2. Variation of fibre density along the length of the beam (sample group S1)

Distribution and orientation of fibres

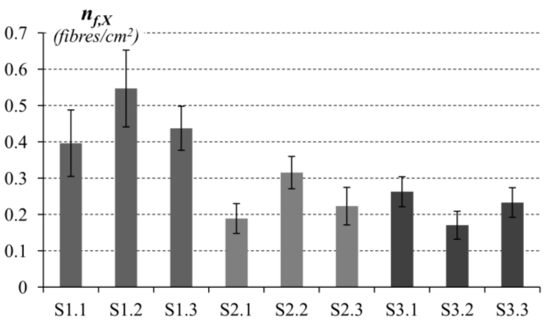
The study of the distribution and orientation of fibres was done in three ranges with respect to the longitudinal direction of the beams. The ranges are: 1) along the whole length of the beam or all X-planes and the regions between them, which allows to evaluate the wall-effect; 2) part of the beam between the planes X_2 and X_{12} to exclude the wall-effect when statistical quantities are calculated; 3) interval between the applied concentrated loads (in four-point bending test), i.e., between the planes X_5 and X_9. This is the region of the maximum bending moment, where cracks are expected to occur. This range is used to study the influence of fibre distribution on initiation of cracks in SFRC beams, discussed later.

The total number of fibres per beam specimen, counted on the surfaces of the cut planes, was from 1006…1156 fibres for group S1, 682…725 fibres for group S2, and 535…625 fibres for group S3. The specimens form groups S1 and S3 had the same nominal fibre amount per volume (80 kg/m3), while the relationship between the number of fibres in group S3 and S1 is 53%, which is due to different cross-sectional areas of the fibres.

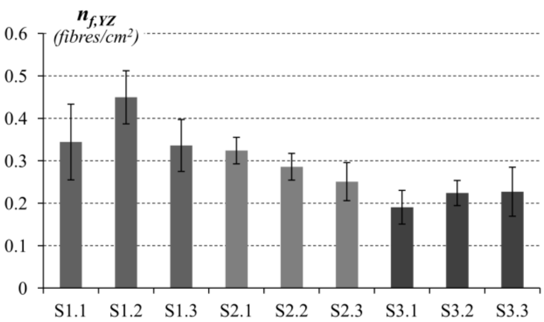
Analysing the obtained data, some characteristics and tendencies of fibre distribution and orientation can be pointed out. First, as it can be expected, there is a tendency for fibres to be oriented more in horizontal position, though a minimal compacting was applied. Considering the horizontal planes, more fibres were in the transversal (crossing Z-planes) than longitudinal (crossing X-planes) direction.

Data dispersion of the fibre density is higher for the specimens with a larger number of fibres (Fig. 3). That leads to comparatively small difference between the properties of the weakest sections, though the average fibre amount is different. Thus, the properties of the weakest section of a SFRC beam, which determines the behaviour of the element under flexure, may not be proportional to the total or average number of fibres per sample. No significant correlation between the number of fibres and the dispersion of fibre orientation was observed.

Variation of fibre orientation within a specimen is rather large. If the ratio of the fibres aligned with the longitudinal direction to the fibres of the transversal direction is considered, the variation coefficient is 0.25…0.42. In this case neither the number of fibres nor the amount of fibres by volume correlate with the variation coefficients of both the fibre density and orientation. The variation coefficient of the fibre density is similar for all specimen groups: 0.2…0.33 for S1, 0.2…0.33 for S2, and 0.23…0.32 for group S3.



(a)



(b)

Figure 3. Mean values of fibre densities in longitudinal (a) and transversal (b) directions and confidential interval for probability of 95%

The results show, that fibres may also align in all directions equally making a particular SFRC element more or less an isotropic material, however, mostly it is not the case. Within a specimen every section may have distinct shapes of the orientation patterns, thus possessing different orientation coefficients.

The variation of the mean values of fibre orientation for the specimens of the same mix is significant for the specimens of groups S2 and S3 with a smaller fibre per volume amount, where the variation coefficients are 0.3 and 0.27 respectively. In the group S1, where the number of fibres per volume is grater, the variation coefficient is as small as 0.08. Relation between mean values of the fibre density in the longitudinal $n_{f,X}$ and transversal $n_{f,YZ}$ directions together with the confidential interval for probability of 95% are shown in Fig. 4.

INFLUENCE OF FIBRE DISTRIBUTION ON CRACK FORMATION

In this section the number of fibres with respect to the fracture plane of the tested beams is analysed. Mean fibre densities per cross-section of the test beams are given in Table 1. The underlined values show the fibre amount in the cracked section. As it can be seen from the data, all cracks formed in the region between the section planes X_5 and X_9, which conforms to the region between the applied forces.

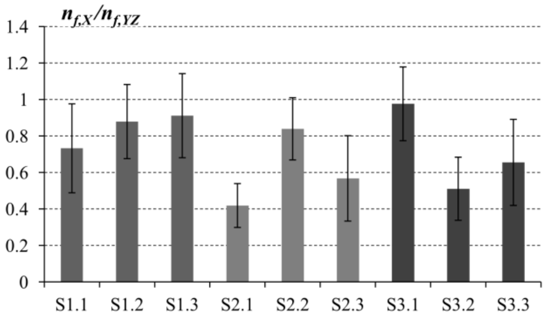


Figure 4. Relation between mean values of fibre density in longitudinal $n_{f,X}$ and transversal $n_{f,YZ}$ directions and confidential interval for probability of 95%

It is assumed that tensile stresses on the most tensioned side are uniform between the applied forces, thus, regarding the stresses, the crack can be expected to appear in any section of this region with equal probability.

On the other hand, the tensile strength of SFRC cannot be considered uniform along the beam, because it is affected by fibre reinforcement, which is randomly distributed with uneven denseness. If the ratio of stresses to strength σ_t / f_t is variable, it is obvious to expect for a crack to initiate in the section where stresses reach the tensile strength first. Besides fibre distribution and orientation, the strength is influenced also by the heterogeneous properties and imperfections of concrete itself.

The fibre density in the crack plane is compared to the densities in other X-planes of the same beam specimen. To evaluate whether fracture plane develops in the section with the smallest number of fibres all section planes located in the range of the maximum bending moment were sorted by the values of fibre density. The sorted planes of each beam with the values of the densities are given in Fig. 4. The bold underlined values indicate the position of the fracture planes.

Fig. 4 shows that there is a strong tendency for cracks to occur in the sections having smaller fibre density. Cracks were never observed in the sections, where the number of fibres was above the mean value. In the case of beams S1.1…S1.3 cracks always developed in the regions with the smallest fibre density. However, for half of the specimens of groups S2 and S3 the weakest sections do not correspond to the planes with the least number of fibres. It is suggested by the authors that the difference is connected with the number of fibres per volume or unit area. As it was observed for the tested beam specimens, the higher mean value of the fibre density, the more explicit the effect of fibres, even if the nominal fibre amount fraction by volume V_f is the same.

Table 1

Fibre densities in *X*-planes

Section number	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
1	0.25	0.38	0.31	0.17	0.14	0.22	0.17	0.23	0.14
2	0.45	0.58	0.59	0.19	0.25	0.23	0.28	0.23	0.23
3	0.39	0.72	0.41	0.16	0.36	0.22	0.27	0.16	0.25
4	0.42	0.61	0.5	0.13	0.44	0.33	0.39	0.16	0.31
5	0.42	0.73	0.23	0.16	0.36	0.31	0.22	0.09	0.25
6	0.61	0.56	0.41	0.20	0.27	0.25	0.28	0.14	0.2
7	0.64	0.28	0.44	0.33	0.28	0.25	0.3	0.16	0.11
8	0.3	0.61	0.45	0.16	0.34	0.16	0.27	0.28	0.22
9	0.28	0.53	0.42	0.25	0.34	0.28	0.2	0.09	0.19
10	0.3	0.38	0.42	0.2	0.27	0.16	0.3	0.19	0.23
11	0.27	0.67	0.44	0.19	0.34	0.19	0.22	0.19	0.33
12	0.28	0.34	0.5	0.13	0.22	0.08	0.17	0.19	0.23
13	0.16	0.17	0.16	0.28	0.17	0.2	0.06	0.13	0.22

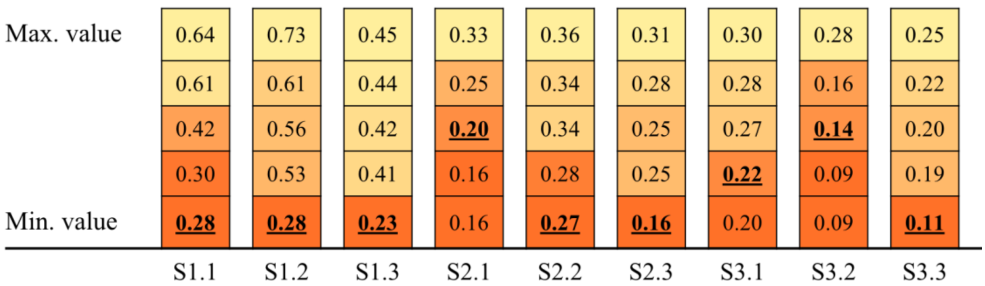


Figure 4. Fibre densities in planes $X_5 - X_9$ of every beam sorted by values of densities, where bold underlined values represent fibre density in fracture plane

Although it is attested that cracking is influenced by fibres, the results show that there are also other factors, which can determine the strength of the section besides the number of fibres per unit area. The orientation, anchorage length, distribution of fibres and imperfections of concrete micro-structure in the particular section of the element can be some of them.

Relationship between the fibre orientation and crack formation was studied as well. The fibres aligned with the longitudinal axis of the beams are considered to have more influence on crack formation than the ones aligned transversally. Therefore, the ratios of fibre density, $n_{f,X}$, registered on *X*-planes to the average fibre density, $n_{f,YZ}$, registered on both *Y*- and *Z*-planes were determined. The fibre densities in transversal directions were calculated as the average of fibre densities in two adjacent regions, which are on both sides of the corresponding *X*-plane. The obtained values are given in Table 2.

To evaluate the influence of fibre orientation on the location of the developed crack, a similar procedure as for evaluating the influence of the fibre density was used. In this case all middle sections (X_5–X_9) were sorted by the values of the ratio of longitudinal to transversal fibres, $n_{f,X} / n_{f,YZ}$. The sorted planes of each beam with the values of the ratio are given in Fig. 5. The bold underlined values indicate the position of the fracture planes.

There is observed a tendency for cracks to develop in sections, where the ratio of longitudinal to transversal fibres is smaller, though the influence is not as strong as of fibre density. However, no crack has occurred in the section planes with the highest value of the ratio $n_{f,X} / n_{f,YZ}$. For two beams the crack occurred in the sections, where the ratio was slightly higher than the mean value. For half of the specimens the fracture planes correspond to the planes, where $n_{f,X} / n_{f,YZ}$ has the minimum value in the considered range. The tendency of a crack to initiate in the sections, where the fibres are less orientated in the longitudinal than in transversal direction, is a bit more pronounced in specimens with higher fibre densities. To analyse the correlation between the influence of orientation of fibres on the crack position and the number of fibres, more investigations of specimens with a wider range of fibre volume fraction V_f are necessary.

Table 2

Ratio of fibre density in longitudinal to transversal directions

Section number	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
2	1.16	1.01	1.21	0.57	0.70	0.79	0.88	0.79	0.75
3	1.43	1.48	1.13	0.50	1.05	0.93	1.06	0.53	0.84
4	1.35	1.30	1.94	0.33	1.51	1.20	1.56	0.64	0.95
5	1.13	1.16	<u>0.77</u>	0.36	1.31	1.08	<u>1.27</u>	0.38	0.73
6	1.32	0.88	1.18	<u>0.49</u>	<u>0.79</u>	0.94	1.24	<u>0.55</u>	0.49
7	1.02	<u>0.57</u>	1.43	0.87	0.74	0.62	0.91	0.65	<u>0.36</u>
8	0.58	1.15	1.04	0.43	0.94	<u>0.40</u>	1.13	1.24	1.47
9	<u>1.03</u>	1.11	0.82	0.73	1.10	1.33	1.37	0.48	1.09
10	0.78	1.20	0.87	0.67	0.95	0.67	1.73	1.00	1.25
11	0.49	1.41	0.95	0.63	1.10	0.65	1.00	0.71	1.20
12	0.45	0.63	1.23	0.36	0.93	0.22	0.81	0.57	0.67

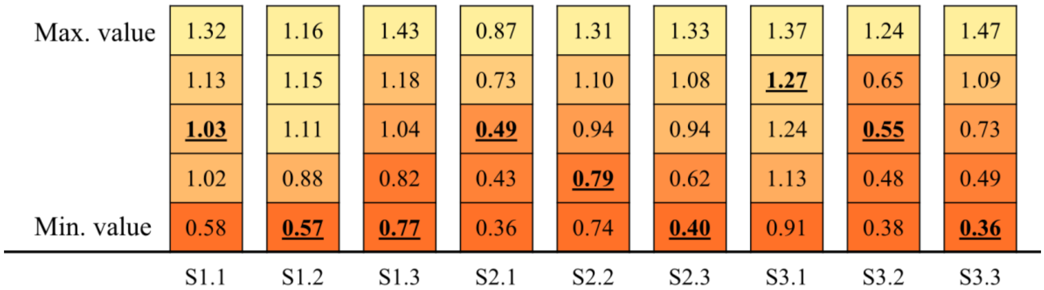


Figure 5. Fibre density ratio of longitudinal to transversal directions ($n_{f,X} / n_{f,YZ}$) in the range between planes X5 – X9 sorted by the values of the ratio, where bold underlined values represent fibre density ratio in fracture plane

NUMERICAL ANALYSIS AND DISCUSSION

From a mechanical point of view, there is an obvious interest in knowing the number of fibres crossing a given cracked section of a structural element. If we assume that the concentration of fibres can be considered as homogeneous, this number is proportional to the total number of fibres per unit of volume multiplied by the parameter α called the orientation factor (Krenchel, 1975; Martinie and Roussel, 2011):

$$n_f = \alpha \frac{V_f}{A_f} \tag{1}$$

where n_f – fibre density;
V_f – fibre volume fraction;
A_f – cross-sectional area of fibres.

The value for α is 0, if no fibre crosses the considered section; α equals 1.0 if all fibres cross the studied section. For isotropic materials α is 0.5. From a simple geometrical point of view, fibres cannot be equally oriented throughout the cross section. If the distance between the wall of a mould and the centre of gravity of a particular fibre is smaller than the half of the fibre length, this particular fibre cannot be orientated perpendicular to that wall. Therefore, the studied cross-section should be divided into at least three zones (bulk, at mould side, and in a corner of the mould) having distinct fibre orientation coefficients.

Dupont and Vandewalle (2005) offer a simple method for calculating the coefficients α for each area of the cross-section, denoting them as α_1, α_2, α_3 for bulk, mould side, and corner of the mould respectively. The overall orientation factor can be calculated as follows by taking the geometrical average over the section:

$$\alpha = \frac{\alpha_1\left(b-l_f\right)+\alpha_2\left[\left(b-l_f\right)l_f+\left(h-l_f\right)l_f\right]+\alpha_3 l_f^2}{bh} \quad (2)$$

where b – width of cross-section;
h – depth of cross-section;
l_f – fibre length.
According to Dupont and Vandewalle the values of the calculated orientation factors are $\alpha_1 = 0.50$, $\alpha_2 = 0.60$, and $\alpha_3 = 0.84$. Applying these values to the prismatic specimens studied in this work, the theoretical orientation factor is obtained, $\alpha = 0.635$. Based on the cross-sectional area of the fibres and the nominal fibre volume fraction, the theoretical fibre density, $n_{f,theor}$, can be predicted. The comparison between the predicted and experimentally obtained fibre densities is given in Table 3. In the table $n_{f,X;mean}$ is the mean value of densities and $n_{f,X,crc}$ is the fibre density in the fracture plane of the tested beams.

Table 3

Theoretically predicted and experimentally obtained fibre densities

Sample	$n_{f,theor}$	$n_{f,X,mean}$	$n_{f,X,crc}$	$n_{f,theor}$ / $n_{f,X,crc}$
S1.1	1.44	0.40	0.28	5.14
S1.2	1.44	0.55	0.28	5.14
S1.3	1.44	0.44	0.23	6.26
S2.1	1.08	0.19	0.20	5.40
S2.2	1.08	0.32	0.27	4.00
S2.3	1.08	0.22	0.16	6.75
S3.1	0.74	0.26	0.22	3.36
S3.2	0.74	0.17	0.14	5.29
S3.3	0.74	0.23	0.11	6.73

Table 3 shows, that the fibre amount predicted by the method, where homogeneous concentration of fibres is assumed, is significantly overestimated in the case of the studied prismatic specimens. Comparing analytically the calculated fibre densities with the average fibre amount in the test specimens, the overestimation is 2.6 to 5.7 times. Furthermore, comparison between the theoretical fibre densities and the densities in the crack planes gives even greater overestimation of 3.3 to 6.7 times (the last column in Table 3).

CONCLUSIONS

The influence of the fibre distribution and orientation on the deformation and strength characteristics of SFRC elements is determined by the fibre counting method on the tested flexural samples sawn into prismatic specimens. It is confirmed that cracks tend to propagate in the regions with a smaller number of fibres and large orientation angles of fibres with respect to the direction normal to the crack plane.
The fibre amount per cross-section, calculated according to the methods assuming that the concentration of fibres is homogeneous, may differ significantly from the actual fibre amount in the section where the crack is located. The method proposed by Krenchel using orientation factors derived by Dupont and Vandewalle gives overestimation of the fibre amount up to 6.7 times in the studied prismatic specimens.

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