FIBRE DISTRIBUTION AND EFFICIENCY IN SFRC

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Abstract

Fibre reinforced structures often exhibit a significant statistical scatter of their response to load especially after the cracks appear. One of the reasons can be a non-uniform distribution of fibres in individual directions. The paper is focused on the distribution of fibres in a standard beams. The experimental program showed that the fibres are distributed preferably in the longitudinal direction, which influences the behaviour of the beams during the loading process. The second part of the research deals with pull out tests of individual fibres. The direction of fibres crossing a possible crack seems to be more important that the anchorage length of individual fibres.

Keywords: Bond, bending, fibres, distribution, pull out, SFRC

1. Introduction

Mechanical properties, the flexural strength in particular, are strongly dependent on the fibre content and fibre orientation in the structural element. The distribution of fibres is influenced by the concrete composition, by the consistency of fresh concrete, by the way of filling the formwork and compaction. In structures it is assumed that the distribution of fibres is uniform in all directions. However, it is difficult to check, how the fibres are actually distributed in the structure. Sometimes it is recommended to cut the specimens (usually prisms) from the structural element, usually in different directions, and then using a destructive testing to estimate the distribution of fibres in individual directions. The flexural strength of SFRC was tested on standard beams using 4 point bending test as recommended in [1]. The results of these tests provided relatively favourable results in terms of the peak load. The experimental program was planned with the objective to investigate the distribution of steel fibres in the standard beams and their effect on results of 4 point bending tests. The other part of the experiment aimed to verify the anchorage of fibres in concrete and to quantify the force necessary for the pull out of fibres.

2. Bending tests

Steel fibre reinforced concrete applied for the production of a precast tunnel lining was taken as an example for verification of the fibres distribution in the laboratory beams of the

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size 150 x 150 x 700 mm. 36 beams were produced in two batches. Additional specimens were cast (cubes and cylinders) which were used for measurement of compression strength and modulus of elasticity. Concrete of the strength class C45/55 XA2 was produced in the mixing plant using a large mixing machine and industrial dosage of fibres. The concrete was taken from the mixer during a standard production. The coarse aggregate with D_{max} = 16 mm was used. The steel fibres of the strength 1500 MPa and of the diameter 1 mm were added in the amount of 35 kg/m^3, which is a rather low level of dosage for load carrying structures. In order to make the compaction easier, relatively flowable concrete was used. The consistency class F3 was used, which means that the slump flow test provides the diameter of spread concrete 420 – 480 mm (measured values 450 and 460 mm).

The specimens were poured into steel moulds and compacted in two steps using a small vibration table (Fig.1). Then they were stored in wet environment and tested at the age 28 and 35 days respectively. At the same age the cubes (150 mm) and cylinders (150 x 300 mm) were tested. The results of the supplementary tests are summarized in the Table. 1.

Fig. 1 Production and compaction of the beams

Tab. 1 Mechanical properties of hardened SFRC

		Batch 1				Batch 2			
		Age 28 days			∅	Age 35 days			∅
Compress. strength $f_{c,cube}$	MPa	61,8	62,3	63,4	**62,5**	62,3	64,8	63,8	**63,6**
Concrete density	kg/m^3	2320	2350	2340	**2330**	2320	2360	2360	**2350**
Modulus of elasticity E_c	GPa	36,0	36,0	36,0	**36,0**	33,0	36,5	34,0	**34,5**

The beams without a notch were subjected to the 4 point bending tests. The loading was controlled by deformation. The rate of deflection was prescribed in accordance with the testing rules 0.2 mm/min. The results of the bending tests are plotted in Fig. 2.

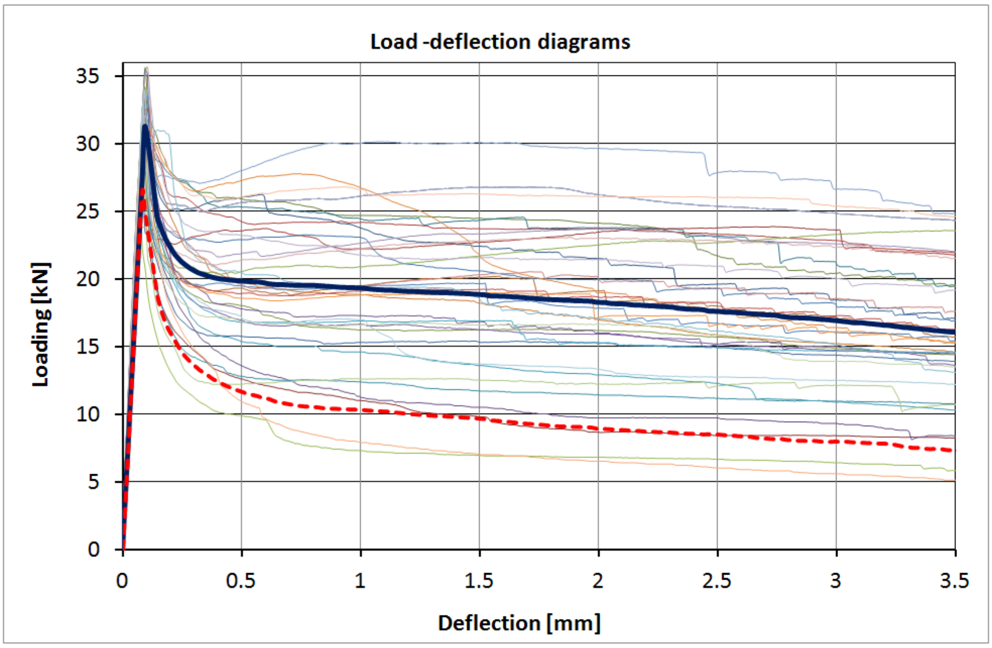

Fig. 2: Load deflection diagrams of the 36 beams. Thick (blue) line = average values, dashed (red) line = characteristic values

The diagrams exhibit a large statistical scatter which is quite usual at SFRC with a small amount of fibres. The average diagram looks very reasonably, the load at the deflection of 3.5 mm is of about 50% of the maximum load, but characteristic load is much smaller at the deflection of 3.5 mm, slightly less than 1/3 of the maximum characteristic load, which is a consequence of the large scatter. The beams were divided into 6 groups of 6 beams and the average results in each group can be seen in the Table 2. The peak flexural strength and the flexural strength at the deflection of 3.5 mm are in the top two lines. The characteristic strength is calculated from the average value taking the scatter into account. On the last line the fracture energy was calculated. This number represents only the energy consumed until the deflection of 3.5 mm is achieved. In fact it is not a complete fracture energy therefore a top index* is used. The numbers are significantly lower than those corresponding to the complete fracture energy which could be approximately 4 times greater.

Tab. 2 Summary of the bending tests results

		Batch 1				Batch 2			
Sets (A-F) Beam no. (1 – 36)		A 1-6	B 7-12	C 13-18	∅	D 19-24	E 25-30	F 31-36	∅
Mean flexural strength $f_{ct,fl}$	MPa	5,7	6,0	5,5	**5,7**	5,7	5,2	5,0	**5,3**
Mean flexural strength (3.5)	MPa	2,5	3,2	2,5	**2,7**	3,0	2,4	2,8	**2,7**
Char. flexural strength (3.5)	MPa	0,9	1,7	1,1	**1,2**	1,5	1,2	0,4	**1,0**
Fracture energy*	Nm	3530	3535	2788	**3284**	3420	2758	3170	**3116**

After bending tests, the beams were cut and cubes of the size 150 mm were produced. The three cubes located in the central part of the beam were then investigated. Non-destructive method of testing was used, and the amount of fibres in the directions x, y, z was measured by the BSM 100 device (Fig. 3). The cubes were installed into the frame of the device in different positions and the amount of fibres in individual directions was measured.

Fig. 3: BSM 100 device for assessment of fibres in individual directions

Before the measurements started, the method was calibrated by repeated measurement on selected cubes. It was concluded that the differences between the individual measurements were almost negligible. However, the measured results are dependent on the temperature and moisture of the environment. Also a position of the crack has to be taken into account and the correct measuring mode has to be adjusted on the device BSM 100. Finally the total number of fibres was checked during the calibration process by destruction of the cube and counting the actual number of fibres. It was concluded that the non-destructive testing provides results with acceptable accuracy.

The three cubes cut from each of the 36 beams were thoroughly investigated by the BSM 100 device and the percentage of fibres located in the directions of x, y, and z was recorded. The device is not able to detect the portion of fibres, which are exactly parallel with the corresponding axis, but it detects those fibres which have an inclination to the corresponding axis small. It can be assumed that the fibres, which are detected in one direction, contribute most significantly just in this direction.

The summary of the results obtained from this observation is evaluated in the Table 3. The results show that the maximum content of fibres was detected in the direction z, which is parallel to the longitudinal axis of the beam. In the transversal and vertical directions, there is also a difference. More fibres are located parallel to the axis x, which is vertical at the position of the beam during the loading process, but horizontal during the casting. It means that during casting most of fibres find its position horizontally and the prevailing direction is parallel to the longitudinal axis of the beam. Such distribution was observed at all beams with a minimum scatter.

The research showed that the fibres are not distributed uniformly. Most of fibres located in longitudinal direction may be a reason for a different performance of the laboratory beams in comparison with larger structures, where the effect of the small specimen is not so characteristic.

Tab. 3 Distribution of fibres in the laboratory beams [%]

	Measured fibre content [kg/m^3]	Fibre content in individual directions [%]		
		X	Y	Z
Mean value	30,1	32,1	16,5	51,4
Maximum	35,7	37,3	21,5	59,4
Minimum	25,0	26,1	12,9	44,6
Standard deviation	2,0	2,7	2,0	3,3

3. Pull out tests

The behaviour of individual fibres in the cracked steel fibre reinforced concrete is important for the performance of complete structures made of SFRC. It provides also necessary information for development of numerical models. The experimental program [2] was focused on pullout tests of individual fibres with different length of anchorage in concrete. The angle of the fibre with respect to the pulling direction was also investigated in two alternatives. The pull out tests of steel fibres of the diameter 1 mm and of the length 60 mm were carried out.

The fibres are installed in small concrete elements. The fibres were installed in the bottom of the formwork in order to fix the fibres in exact position. In one element always 16 fibres are anchored. The fibres in vertical position (direct pullout) have two anchorage lengths – 50% of the fibre length (30 mm) and 25% of the length (15 mm). The last series included the fibres inclined by 45°, which were anchored on 50% of their length (30 mm). The fibres in the mould before casting are plotted in Fig. 4.

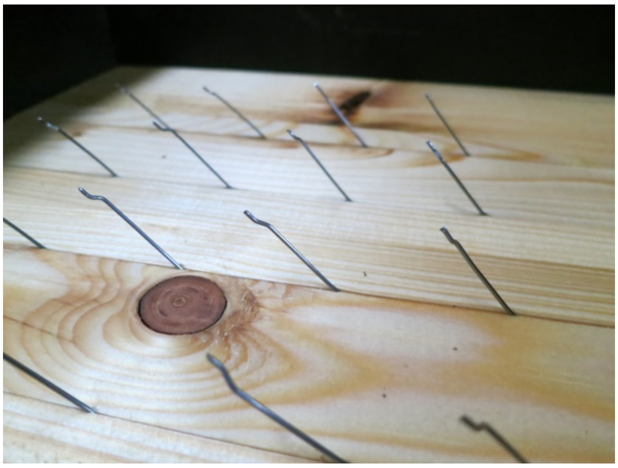

Fig. 4: The inclined fibres in the bottom of the mould before casting

A typical diagram of the pullout test is plotted in Fig. 5. The fibres were pulled out under the displacement control. Fig. 5 shows the diagram of fibres which were vertical with the anchorage length 15 mm. The results show that the statistical scatter of the 16 curves is relatively reasonable. All the fibres failed by pulling out of concrete and no fibres failed in steel.

Very similar diagrams were obtained in the case if the anchorage length was increased to 30 mm. The maximum pulling force is very similar for anchorage length 15 and 30 mm.

The longer anchorage length increases the pulling force of about 5%. On the other hand the fibres which were inclined exhibited a larger resistance about 25%. However, about 50% of fibres failed by breaking of the steel fibre.

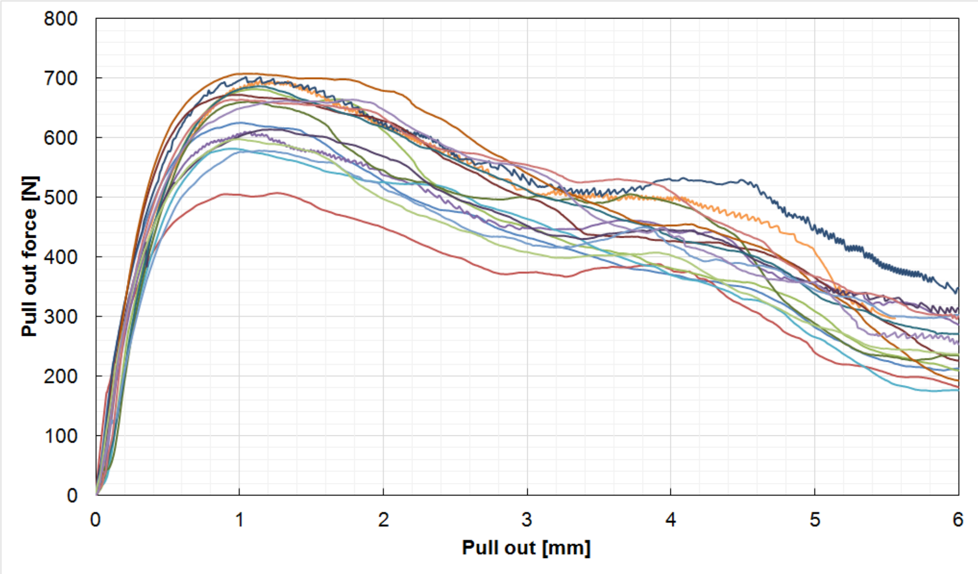

Fig. 5: Load displacement diagram of the pullout tests (1 specimen with 16 fibres, 15 mm anchorage length)

4. Conclusions

The experimental programs showed that the fibre reinforced concrete is sensitive to the distribution of fibres. The fibres in laboratory beams were not distributed uniformly. The most of fibres are parallel to the longitudinal axis of the beam. Then the laboratory results need not completely correspond to the actual performance of structural elements. The reason for this result can be found in the lower consistency of the concrete and the compaction of the specimens using a vibrating table.

The pull out tests showed that the inclined fibres (with respect to the crack) are more resistant than the fibres located perpendicular to the crack. The tests showed that the fibres work rather consistently and no large differences between the pullout curves were obtained.

Acknowledgement

The research was supported by Competence Centres program of Technological Agency of the Czech Republic (TA CR), project no. TE01020168.

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