Variation of bending strength of fiber reinforced concrete beams due to fiber distribution and orientation and analysis of microstructure

H Herrmann¹, R Boris², O Goidyk¹ and A Braunbrück¹

¹ Tallinn University of Technology (TalTech), School of Science, Department of Cybernetics, Ehitajate tee 5, 19086 Tallinn, Estonia

² Vilnius Gediminas technical university, Institute of Building Materials, Laboratory of Composite Materials, Linkmenu str. 28, 08217 Vilnius, Lithuania

E-mail: hh@cens.ioc.ee, renata.boris@vgtu.lt

Abstract. Fiber reinforced concrete is becoming increasingly popular as a construction material, as it can potentially form a ductile concrete. The properties of the fiber reinforced concrete depend on the concrete recipe, the flow of the fresh concrete into the formwork, possible vibrating of the concrete and the fiber orientations.

This contribution presents the results of bending tests performed on fiber reinforced concrete beam specimens, which have been cut out of a larger plate. These beams have different fiber orientation distributions, due to being taken from different parts of the plate and with different orientation with respect to the flow of the fresh concrete. Further, the microstructure of the concrete was investigated using scanning electron microscopy (SEM). The SEM shows no obvious differences in the microstructure between beams of different strength and shows good adhesion of fiber and concrete matrix in all investigated samples.

1. Introduction

The use of fiber reinforced concrete (FRC) is becoming increasingly popular, especially in the casting of concrete floors, here, short steel or plastic fibers or both, provide for the concrete floor resistance to drying shrinkage cracks.

Apart from concrete floors, other load-bearing elements retain some conventional reinforcement, even when cast with fiber reinforced concrete. The structural integrity of an element cast purely of fiber reinforced concrete still has questions to be answered in full. How, for example, the casting conditions—like flow of the fresh concrete and fiber orientations— influence the strength and ductility of the hardened fiber reinforced concrete? Some answers could be found partly in the previous research, for instance, the spatial and orientational fiber distribution within a concrete beam is to a large degree depending on formwork surface quality [1–3] and wall-effect [2, 4] and the casting methods.

There are a several methods to investigate the durability characteristics of the materials, to determine the coupling bonds and the weakest places inside of concrete mass and to analyze the post-cracking behavior. Many research groups have applied three-point or four-point bending tests [5, 6], compression test [7] and pull-out test [8, 9].
To correlate the obtained results from the experiments with the existing fiber orientation, the Computed Tomography technique is widely applied. Recently, use of X-ray Computed Tomography (CT) in civil engineering research is becoming quite popular. X-ray CT is an advanced nondestructive method that have been widely used for obtaining 3D images of the internal micro-structure of the objects [10–13]. This technique allows to get the information about defects in the concrete structure, such as pores, micro-cracks and enables to determine the fiber orientation and spatial distribution inside of the non-transparent concrete matrix [14–17].

The expected influence of the fiber orientation distribution has been highlighted before [18–22]. Numerical simulations can used to predict the fiber orientation and distribution during the manufacturing process [2,3,23,24] and the influence on mechanical properties [25].

This paper reports recent test results on the local strength and ductility of the short steel fiber reinforced self-compacting concrete (SFRSCC). By cutting a larger plate to smaller beams and testing the beams, local strength characteristics of the large plate can be obtained. The 4-point bending test, makes it possible to subject a considerable amount of the beam volume to constant bending moment, determining this way the weakest place and path for the cracks to occur. The orientation of the cut-out beams has been chosen according to the plate casting direction and movement. For comparison a similar pure self-compacting concrete (SCC) plate was cast and tested.

2. Experiments
2.1. Casting of Plates, Materials and Mix Design
A detailed description of the experimental setup and procedure can be found in [26]. Here a summary is presented. The experimental study was performed on two different mixtures: a pure self-compacting concrete (SCC) and short steel fiber reinforced self-compacting concrete (SFRSCC). Both concrete plates were produced by the manufacturer according to the recipe. The main mixture components are presented in table 1. The mixing was carried out according to normal factory procedure in a production-line mixer with a capacity of 1–2 tons.

| Table 1. Composition of SCC mix, amount mixed: 1 qm. |
|-----------------------------------------------|
| Cement (kg)                        | 330 |
| Sand (0-2mm) (kg)                  | 398 |
| Sand (0-4mm) (kg)                  | 505 |
| Crushed Stone (2-5) (kg)           | 336 |
| Crushed Stone (8-11) (kg)          | 539 |
| Filler (kg)                        | 80  |
| Admixture (kg)                     | 5.1 |
| Water (kg)                         | 175 |
| Fibers (SFSCC only)(kg)            | 50  |
| extra water (SFSCC only)(kg)       | ~10 |

The main aim of mixing procedure is to obtain a proper consistency and viscosity, cohesive and uniform structure of the fresh concrete mixture. The SFRSCC and SCC mixes were practically identical with the only difference that for SFRSCC the amount of water was slightly higher in order to get the rheological properties of SFRSCC and SCC to be roughly equal and within the required guidelines.

The volume fraction of steel fibers was 1%. The basic characteristics and properties of selected fibers are presented in table 2.

After intensive mixing, the slump flow tests were performed for each mixture. In the case of SCC spread of the slump was 700 mm, in the case of SFRSCC the diameter was 650 mm.
Table 2. Data of the steel fibers, according to [27].

| Property                          | Value                           |
|-----------------------------------|---------------------------------|
| Manufacturer                      | Severstal Metiz                 |
| Model                             | Hendix prime 75/52              |
| Type                              | hooked end                      |
| Length, mm                        | 52 ± 2.0                        |
| Diameter, mm                      | 0.75 ± 0.04                     |
| Hook length, mm                   | 2.0 − 1.0/ + 2.0                |
| Hook height, mm                   | 2.1 + 0.5/ − 0.0                |
| Bend angle, degrees               | 40 ± 5                          |
| Tensile strength, MPa             | 1500                            |
| Elastic modulus, MPa              | ≥ 190000                        |
| Number of fibers per kg, pcs.     | ~ 5545                          |

Then the casting was carried out. The fresh concrete mixtures were poured into beforehand prepared, foil covered wooden molds. In both cases the bucket was used as a filling method, that moved in the longitudinal direction. Both casting processes were recorded with a camera to enable the subsequent analysis.

Further, instantly after the casting procedure to align the specimen surfaces the special tools were used. After that, to provide the easy unmolding, lifting and transportation of the slabs, lifting anchors were placed into the concrete mass. Then the slabs were left to harden in the manufacturing hall at room temperature.

Standard compression tests have been performed on separately cast cubic test specimen, the concrete for these was taken out of the mass for the plates during casting.

2.2. Preparation of Beam Specimen

The experimental analysis in the present research includes 4-point bending tests and Computed Tomography with the aim to determine the fiber orientation and distribution inside the concrete slabs and its influence on the strength of the concrete. For this purpose, the produced large slabs with dimensions \((L \times W \times H)\) 400 cm × 100 cm × 10 cm were cut into smaller beams. Namely, from the slab of SCC 10 beams of size 100 cm × 9.5 cm × 10 cm have been cut out and the slab of SFRSCC has been cut into 40 beams of size 100 cm × 9.5 cm × 10 cm. The schematic layout of the specimens cut out of the big slabs is shown in figure 1.

2.3. The Bending Test set-up

All 40 beams of SFRSCC and 10 beams of SCC were tested by a 4-point bending test. During the bending test the following quantities were registered: the load, the mid-span displacements. From this, the post-cracking behavior and the force-displacement curves were obtained.

All experimental devices and the testing specimen dimensions are presented in figure 2 (photo) and figure 3 (drawing).

Full description of the set-up and details of bending test procedure are described in [26].

All specimens were subjected to the analogous loading procedure until the displacement reached a maximum 10 mm. The specimen have been over 4.5 months old at the time of testing and the effect of the difference in age at the time of testing should be negligible.

2.4. Tomography

The current research is mostly focused on the influence of the casting process on the fiber orientation and positions inside of the big-size plate of SFRSCC. In addition, by using X-ray
CT scanning the hypothesis that certain fiber orientation inside of concrete beam improves the post-cracking behavior of SCC will be verified. For these purposes, so far four beams were chosen, according to figure 4. According to the expectations from casting simulations, fiber beams 10 should have fibers well aligned along the beam axis, due to the wall-effect, and beams 21, 36 and 38 should have changing orientation of the fibers along the axis, with fibers being perpendicular to the beam axis at the ends of the beams and parallel to the axis in the middle of the beams. However, beam 21 is still in the casting path of the bucket and beam 36 close to the end of the casting path. Therefore, disturbed fiber alignment can be expected. The beams have been chosen, to verify the fiber alignment in different sections of the plate. The scanning of the beams was performed with a resolution 0.6 mm. In the future further beams will be scanned.
2.5. X-ray diffraction and SEM
The X-ray diffraction (XRD) analysis of the phase composition of materials was carried out upon applying diffractometer DRON-7 (Russia). In order to obtain X-ray radiation Cu Kα spectrum ($\lambda = 0.1541837$ nm), a graphite monochromator was used. The parameters of the tests were following: voltage: 30 kV; current: 12 mA; the range of the diffraction angle: from 4 to 60°; the detector movement step: 0.02°; the duration of the intensity measuring in a step: 0.5 s. Phase identification was carried out by decoding the XRD patterns according to ICDD diffraction databases. The microstructure of the materials was explored upon use of scanning electron microscopy (SEM) equipment JEOL JSM-7600F (Japan). The parameters of electron microscopy were following: voltage: 10 kV; the distance to the surface of the specimen: from 17 to 20 mm. The peculiarities of the microstructure were identified on examining the split surface of the specimens. The image was formed on registering the signal of secondary electrons. Before testing, the surface was coated with electrically conductive thin layer of gold by evaporating the gold electrode in the vacuum using the instrument QUORUMQ150R ES (Germany).

3. Results
3.1. Compression Tests
The results of the standard compression test are presented in table 3 and figure 5. It is interesting to note, that the compressive strenght of the SFRSCC cubes was lower than that of the SCC. Part of this difference can be accounted for by the small difference in the water-cement ratio, but probably this does not account for the full difference.

3.2. Bending Tests
The results of the bending tests in figure 6 show small variations in the load at first crack, but a large variation in the post-cracking behaviour. The post-cracking behaviour shows a
Table 3. Results of compression tests for SCC and SFRSCC.

| age at test in days | 4   | 7   | 28  |
|--------------------|-----|-----|-----|
| # of samples       | 3   | 3   | 10  |
| $\bar{\rho}$ in kg/m$^3$ | 2330 | 2340 | 2379 |
| stdev in kg/m$^3$   | 0   | 30  | 9   |
| $\bar{\sigma}_{u,c}$ in MPa | 54.1 | 55.3 | 68.6 |
| stdev in MPa        | 2   | 1   | 2   |

| # of samples       | 3   | 3   | 10  |
|-------------------|-----|-----|-----|
| $\bar{\rho}$ in kg/m$^3$ | 2357 | 2370 | 2382 |
| stdev in kg/m$^3$   | 12  | 10  | 14  |
| $\bar{\sigma}_{u,c}$ in MPa | 44.9 | 45.5 | 56.6 |
| stdev in MPa        | 0   | 1   | 1   |

Figure 5. Compressive strength of SCC and SFRSCC.

strong strain-softening for some beams, notably for beams taken from casting path, and strain-hardening behaviour for other beams, notably the edge beams.

3.3. Tomography

The image processing of the tomography images was carried out using 3D Slicer which is an open-source platform developed for registration, segmentation and 3D visualization of medical imaging data [28].

The main objective of the image processing was to visually analyze the micro-structure of the beams; to obtain the high quality images of fiber orientation and distribution and the formed crack outlines inside of the testing specimens. Generally, the image processing technique allows to efficiently separate the investigated objects (fibers) from the background, to detect the air voids and another defects and to minimize the noises from the images.

The image processing mainly involves several steps: the contrast enhancement and thresholding. Firstly, in order to obtain the improved separation between the background and fibers, the intensity and opacity thresholds were applied. The typical examples after image
Figure 6. Load-displacement diagrams for some of the tested beams.

Visually, it is possible to see a difference in the fiber alignment between beams 10 and 21,
figure 7. In beam 10 the fibers show a strong tendency to align along the beam axis, while in beam 21 the fiber orientations are more random.

3.4. XRD analysis
Characteristic diffraction curve of the SFRSCC in all specimens (1, 2, 33 and 35) obtained by XRD analysis is presented in figure 9. It can be seen from the XRD analysis that after hardening, ettringite \((3\text{CaO} \cdot \text{Al}_2\text{O}_3 : 3\text{CaSO}_4 : 31\text{H}_2\text{O})\), calcite \((\text{CaCO}_3)\), portlandite \((\text{Ca(OH)}_2)\), C-S-H \((n\text{CaO} \cdot \text{SiO}_2 : m\text{H}_2\text{O})\), feldspars \((\text{KAlSi}_3\text{O}_8 - \text{NaAlSi}_3\text{O}_8 - \text{CaAl}_2\text{Si}_2\text{O}_8)\) and quartz \((\text{SiO}_2)\) minerals were identified in the SFRSCC.

![Figure 9](image)

**Figure 9.** Representative diffraction curve of the steel fiber reinforced concrete: Q - quartz, K - calcite, P - portlandite, E - ettringite, C - C-S-H, F - feldspars.

3.5. SEM analysis
The morphology of the SFRSCC is visible in SEM images of the cut surface of the specimens 1 and 35 (figure 10). SEM results employed to evaluate the effect of steel fiber used on the development of SFRSCC. Figure 10 illustrates a very good contact of steel fiber with the binder and it does not depend on the orientation of the fiber and position of specimen. Microstructure tests revealed that specimens have a dense structure.

A representative image of the binding material in all specimens obtained by SEM analysis is presented in figure 11. The image reveals the prevalence of rhomboid shaped calcite minerals, plate shaped portlandite, fibre shaped ettringite and the formed C-S-H crystals, similar to a cellular frame carpet.

As SEM and XRD tests show (figure 9 and 11) the same hydrates are formed in the specimens (1, 2, 33 and 35). It can be seen from the XRD and SEM tests a very good contact of steel fiber with the concrete binder is present in all specimens.
Figure 10. SEM images of the contact zone of steel fiber and binder: a) specimen 1, b) specimen 35.

Figure 11. Representative SEM image of the binding material in the tested specimens.

4. Discussion of Results
The 4-point bending tests show a large variability in the post-cracking strength, depending from which position in the plate the beam was taken from. The variability is much larger than for ordinary reinforced concrete. The microstructure investigation showed the same concrete microstructure and good fiber-concrete adhesion in all samples. The X-ray tomography showed differences in the fiber orientations and the fiber orientation distribution, while no obvious
correlation to the fiber amount is visible. The differences in the post-cracking strength show some correlation with the fiber orientations.

5. Ongoing and Future Investigations
The analysis of fiber orientations by use of X-ray Computed Tomography (CT) has not been finished. Further selected beams will be scanned using CT and the fiber positions and orientations will be extracted from the volume image. Special attention will be paid to the cracked region. The results of the fiber orientation measurements will be compared to computational fluid dynamics simulations of the fiber orientations.

6. Conclusion
In this paper the results of four-point bending tests performed on beam specimens cut out of a large plate have been presented. The initial results are that in all beams fibers improve fracture behaviour compared to SCC, although the actual post-cracking performance depends on the position within the plate where the sample was taken from. The results coincide (roughly) with expectations from predicted fiber orientation distribution in samples, which seems to confirm that the flow of the fresh concrete mass influences fiber orientations. The microstructure analysis by SEM and XRD did not reveal differences between the samples that could account for the difference in fracture behaviour. This leads to the conclusion, that the bending results are very sensitive to the casting procedure. It follows, therefore, that SFRSCC properties of specifically produced small-scale laboratory samples may not be representative for large structural elements – such scale-dependence stands in contrast to the properties of SCC. Further, one can conclude that special care is needed to design casting technologies and methods which will produce consistent fiber orientation distributions and that on-site casting may be problematic.

Acknowledgments
This work was supported by the Estonian Research Council grant (PUT1146). Support through the exchange program by the Estonian and Lithuanian Academies of Sciences is gratefully acknowledged.

Thanks to E-Betoonelement for preparing the experiment plates, space for cutting the beams and their general interest in the research. We also thank Elmar-Jaan Just and Peeter Linnas of the Department of Civil Engineering and Architecture, School of Engineering, for letting us use the equipment in the Mäepealse lab.

References
[1] Herrmann H, Goidyk O and Braunbrück A Influence of the flow of self-compacting steel fiber reinforced concrete on the fiber orientations, a report on work in progress 2019 Short fiber reinforced cementitious composites and ceramics ed Herrmann H and Schnell J (Springer) pp 97–110
[2] Herrmann H and Lees A On the influence of the rheological boundary conditions on the fibre orientations in the production of steel fibre reinforced concrete elements 2016 Proc. Estonian Acad. Sci. 65 408–413 open-Access CC-BY-NC 4.0
[3] Svec O, Zirgulis G, Bolander J E and Stang H Influence of formwork surface on the orientation of steel fibres within self-compacting concrete and on the mechanical properties of cast structural elements 2014 Cem. Conc. Compos. 50 60–72 ISSN 0958-9465
[4] Suuronen J P, Kallonen A, Eik M, Puttonen J, Serimaa R and Herrmann H Analysis of short fibres orientation in steel fibre reinforced concrete (sfc) using x-ray tomography 2012 J. Mater. Sci. 1–10 ISSN 0022-2461 online-first
[5] Ponikiewski T, Katzer J, Bugdol M and Rudzki M X-ray computed tomography harnessed to determine 3d spacing of steel fibres in self compacting concrete (scc) slabs 2015 Construction and Building Materials 74 102–108 ISSN 0956-7151
[6] Herrmann H, Braunbrück A, Tuisk T, Goidyk O and Naar H An initial report on the effect of the fiber orientation on the fracture behavior of steel fiber reinforced self-compacting concrete 2019 Short fiber reinforced cementitious composites and ceramics ed Herrmann H and Schnell J (Springer) pp 33–50

[7] Oesch T S, Landis E N and Kuchma D A Conventional concrete and uhpc performance–damage relationships identified using computed tomography 2016 Journal of Engineering Mechanics 142 04016101

[8] Oesch T 2016 6th Conference on Industrial Computed Tomography, Wels, Austria (iCT 2016)

[9] Macanovskis A, Lusis V and Krasnikovs A Crack opening investigation in fiberconcrete 2014 World Academy of Science, Engineering and Technology 8 430–438

[10] Pittino G, Geier G, Fritz L, Hadwiger M, Rosc J and Pabel T Computertomografische untersuchung von stahlfaserspritzbeton mit mehrdimensionalen transferfunktionen 2011 Beton- und Stahlbetonbau 106 364–370 ISSN 1437-1006

[11] Promentilla M, Sugiyama T and Shimura K 2008 3rd ACF International Conference ACF/VCA pp 940–947

[12] Schnell J, Schladitz K and Schuler F Richtungsanalyse von fasern in betonen auf basis der computertomographie 2010 Beton- und Stahlbetonbau 105 72–77 ISSN 1437-1006

[13] Vicente M, Minguez J and González D The use of computed tomography to explore the microstructure of materials in civil engineering: From rocks to concrete 2017 Computed Tomography - Advanced Applications ed Halefoglu D A M (InTech)

[14] Mishurova T, Léonard F, Oesch T, Meinel D, Bruno G, Rachmatulin N, Fontana P and Sevostianov I 2017 Proceedings of the 7th Conference on Industrial Computed Tomography (ICT) held February 7-9, 2017, Leuven, Belgium vol 22(03) (NDT.net) ISSN 1435-4934 http://www.ndt.net/?id=20818

[15] Oesch T S 2015 Investigation of Fiber and Cracking Behavior for Conventional and Ultra-High Performance Concretes Using X-Ray Computed Tomography Ph.D. thesis University of Illinois at Urbana-Champaign

[16] Ponikiewski T, Katzer J, Bugdol M and Rudzki M Steel fibre spacing in self-compacting concrete precast walls by x-ray computed tomography 2015 Mater. Struct. 48 3863–3874 ISSN 1359-5997

[17] Vicente M A, Gonzalez D C and Minguez J Determination of dominant fibre orientations in fibre-reinforced high-strength concrete elements based on computed tomography scans 2014 Nondestructive Testing and Evaluation 29 164–182

[18] Herrmann H and Engelbrecht J Comments on mesoscopic continuum physics: Evolution equation for the distribution function and open questions 2012 Proc. Estonian Acad. Sci. 61 71–74 ISSN 1736-6046

[19] Herrmann H 2016 Generalized Continua as Models for Classical and Advanced Materials (Cham: Springer International Publishing) chap An Improved Constitutive Model for Short Fibre Reinforced Cementitious Composites (SFRC) Based on the Orientation Tensor, pp 213–227 ISBN 978-3-319-31721-2

[20] Eik M, Herrmann H and Puttonen J 2015 Proceedings of the XII Finnish Mechanics Days : [4-5 June 2015, Tampere, Finland] ed Kouhia R, Mäkinen J, Pajunen S and Saksala T pp 255–260 ISBN 978-952-93-5608-9

[21] Eik M, Puttonen J and Herrmann H The effect of approximation accuracy of the orientation distribution function on the elastic properties of short fibre reinforced composites 2016 Compos. Struct. 148 12–18 ISSN 0263-8223

[22] Herrmann H and Beddig M Tensor series expansion of a spherical function for use in constitutive theory of materials containing orientable particles 2018 Proc. Estonian Acad. Sci. 67 73–92 open-Access CC-BY-NC 4.0

[23] Zirgulis G, Svec O, Geiker M R, Cwirzen A and Kanstad T Influence of reinforcing bar layout on fibre orientation and distribution in slabs cast from fibre-reinforced self-compacting concrete (frscc) 2016 Structural Concrete 17 245–256

[24] Krasnikovs A, Kononova O, Khabsa A, Mačanovskis E and Mačanovskis A Post-cracking behaviour of high strength fibre concrete predictor and validation 2011 World Academy of Science, Engineering and Technology 988–992

[25] Herrmann H, Eik M, Berg V and Puttonen J Phenomenological and numerical modelling of short fibre reinforced cementitious composites 2014 Meccanica 49 1985–2000 ISSN 0002-6455

[26] Herrmann H, Goidyk O, Naar H, Tuisk T and Braunbrück A The influence of fiber orientation in self-compacting concrete on 4-point bending strength 2019 Proc. Estonian Acad. Sci. 68 open-Access CC-BY-NC 4.0, forthcoming

[27] Severstal Metiz 2018 Hendix prime 75/52 - hooked ends fiber http://www.severstalmetiz.ru/eng/catalogue/1930/document6219e.shtml?6605,1

[28] Pieper S, Halle M and Kikinis R 2004 3d slicer IEEE International Symposium on Biomedical Imaging ISBI 2004