# VARIATION IN TENSILE BEHAVIOUR OF FIBRE REINFORCED CONCRETE

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## Abstract

*The Institute of Structural Concrete at Graz University of Technology studied the variation of tensile behaviour of fibre reinforced concrete systematically. The research program includes 48 four-point-bending tests to determine the tensile behaviour, three – 2.5 m long - beams and a cellar, which consists of a base plate and two rising walls, to consider realistic conditions. To achieve information on the influence of casting, specimens were cut out of the long beams and at several locations of slab and walls of the cellar. On those specimens fibre number and orientation was determined with an opto-analytic method and bending tests were performed.*

*The four-point-bending test series shows a high variation in the post-cracking behaviour. The surprising finding was independence of this variation from fibre length and consistency of fresh concrete. This contribution further shows the investigation result of the beams and the cellar and explains the observed variation of tensile strength by comprehensive analysis.*

**Keywords: fibre concrete, tensile behaviour, bending test, steel fibre, fibre orientation**

## 1. Introduction

Steel fibre reinforced concrete has been successfully used in Europe for over 30 years in certain areas of concrete construction. Its applications range from shotcrete and prefabricated concrete products, to monolithic basements and tunneling. However, the main area of application is still industrial concrete floor slabs [1]. The reason for this is the large dispersion in the post cracking tensile behaviour. The present experimental data clarifies the variation in tensile behavior of fibre reinforced concrete (FRC) based on four-point bending tests. The large dispersion makes a design concept for supporting components difficult since the introduction of significant safety factors is necessary. For design, the already low characteristic values (5%-fractile) are divided by safety factors. It is difficult to handle replacement of conventional reinforcement or crack width limitation with those low design values.

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Numerous studies show a strong correlation between the number of fibres in the cross-section and the observed post cracking behavior of each specimen [2], [3], [4]. Due to this, the dispersion in tensile behavior is caused by the variation in fibre distribution and orientation. In order to clarify these issues this paper focuses on the scattering in post cracking tensile behaviour of FRC under laboratory and construction side conditions.

The paper and the experimental program are divided into three parts: At first, four-point-bending tests were carried out to determine the tensile behaviour. Secondly, 3 long beams with a length of 2.5 m were cast in various manufacturing methods to explore the distribution and orientation of fibre along the beams. Finally, a cellar consisting of a base plate and two rising walls, was manufactured to consider realistic conditions.

## 2. Basics

Due to the variety of different factors, it is not possible to draw conclusions from the quantity of fibres used and the selected concrete compressive strength class, to draw reliable conclusions on the post-cracking behaviour. Appropriate procedures have been developed for the analysis and classification of the post cracking tensile strength. Direct tensile tests proved as inappropriate due to the high costs and large sensitivity to variations in the experimental setup. The guideline ‘Faserbeton’ (Fibre Reinforced Concrete) [5] by the German Committee for Structural Concrete defines at least 6 bending beams with dimensions l/w/h=70 x 15 x 15 cm for the determination of tensile behaviour. The bending test results can be used to recalculate the direct tensile strength in the ultimate and serviceability limit state. For the serviceability limit state the stress at a mid-span deflection of 0.5 mm is decisive, for the ultimate limit state the stress at a mid-span deflection of 3.5 mm. Consequently, bending tests are used in this paper.

Fibre orientation and fibre distribution influence the post cracking tensile behavior. Without external interference, the fibres distribute three-dimensional freely and randomly in space. Casting and manufacturing technology, limitations by framework surfaces, vibration, settling of the fibres at unsuitable properties of fresh concrete and the maximum aggregate size affect the fibre distribution and orientation. In the edges and corners of switched components, fibres can only orientate two-dimensionally due to physical reasons [1].

In this research, an otpoanalytic method [6] was used to determine the fibre distribution and orientation at specified positions of the long beams and the cellar. The specimens are cut from the components, photographed and evaluated by computer support. To take into account the fibre orientation, the fibre orientation factor $\eta_F$ has been established and can be determined for a sectional area as follows [6]:

$$h = \frac{1}{N_F} \sum_{i=1}^{N_F} \frac{d_{F,i}}{d_{F2,i}} \qquad (1)$$

The orientation factors for 1D, 2D and 3D distribution are [7]:

- 1D distribution 1.0
- 2D distribution $2/\pi \approx 0.637$
- 3D distribution 0.5

## 3. Experiments on small-sized beams

A series of 48 four-point-bending tests was carried out in order to study the bending behaviour and the variation of bending parameters of normal fibre concrete. Four different types of fibre concrete have been included in this part, which have been altered by the fibre length (25 mm, 50 mm) and the spread value (F4, F6). The spread value F4 corresponds to a slump of 49-55 cm, F6 of 63-70 cm.

### 3.1 Test setup an procedure

Three bending beams were cast for each of the four series. In order to investigate the variation of bending parameters, each series was carried out four times (on four different days), thus 48 specimens in total. The mixing procedure and the casting method were not varied throughout the research, in order to maintain consistency. All the beams have been cast from one end of the formwork and were compacted by a vibrating table.

The mix composition of the materials used in chapter 3 and 4 of this paper is shown in Tab. 1. The fibre content was 30 kg/m³. Two types of straight steel fibres with hocked ends were used. Fibre type I (length 25 mm) and II (length 50 mm) are characterized by a diameter of 0.6 mm and a tensile strength of 1100 N/mm².

Tab.1: Concrete mixture [kg/m³]

| Component | M1 | M2 | M3 | M4 |
|---|---|---|---|---|
| CEM I 42,5 R | 300 | 300 | 300 | 300 |
| Fly ash | 75 | 75 | 75 | 75 |
| Water | 174 | 174 | 174 | 174 |
| Sand 0/4 mm | 708 | 708 | 708 | 708 |
| Gravel 4/8 mm | 359 | 359 | 359 | 359 |
| Gravel 8/16 | 738 | 738 | 738 | 738 |
| Superplasticizer | 4.9 | 8.7 | 4.9 | 8.7 |
| Steel fibre WLS-25/0.6/H | 30 | 30 | | |
| Steel fibre WLS-50/0.6/H | | | 30 | 30 |

Cylindrical and cubic specimens were used to determine the compressive strength as well as the elastic modulus for the concrete. As expected, the different fractions of steel fibres did not have a significant influence on the material strength. The strength of concrete was characterized as C30/37 with an elastic modulus of $E_c$ = 35000 N/mm².

All 12 beams of each type of concrete have been tested at an age of 28 days. The test setup corresponding to the guideline 'Faserbeton' (Fibre Reinforced Concrete) [5] by the German Committee for Structural Concrete was used in this research. The test setup is illustrated in Fig. 1. The specimens were rotated by 90° so the top surface during casting faced sideways during testing. It should be noted that the specimens have been supported by steel bars to ensure low horizontal forces due to support friction. The specimens have been tested according to the guideline 'Faserbeton' [5]

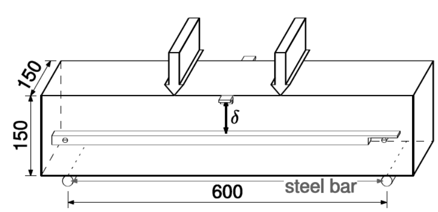


Fig. 1: Bending test specimen and setup

### 3.2 Results & Discussion

The equivalent bending stress – mid-span deflection relationship for all concrete mixes with steel fibres is given in Fig. 2 and 3. Fig. 2 illustrates test results of M1 and M2, including 25 mm fibres and a fresh concrete consistency of F4 and F6. Fig. 3 shows test results of M3 and M4 including 50 mm fibres and same consistencies.

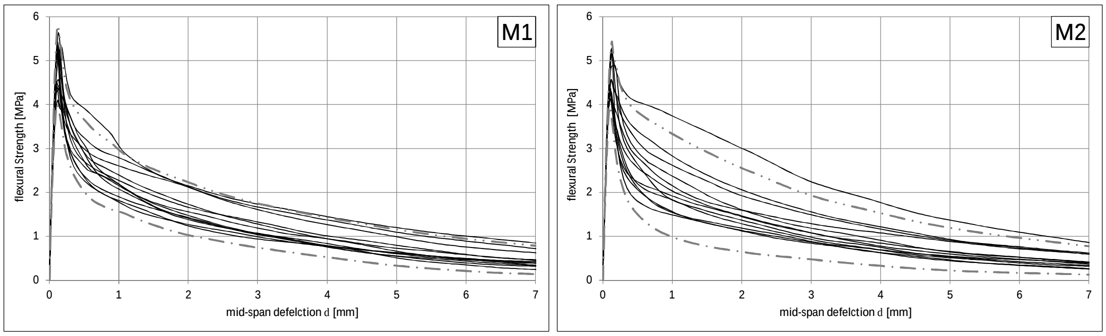


Fig. 2: Bending stress – mid-span deflection of M1 and M2 (fibre 25 mmm)

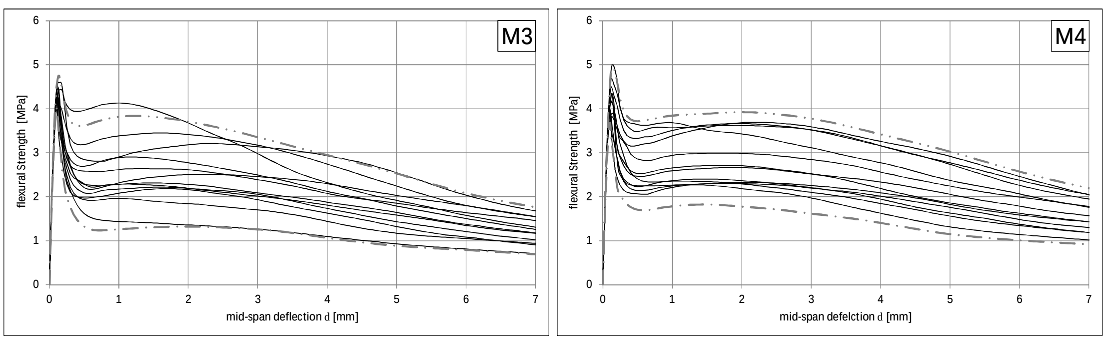


Fig. 3: Bending stress – mid-span deflection of M3 and M4 (fibre 50 mmm)

The sub-critical fibre content of 30 kg/m³ is resulting in deflection softening behaviour. When the tensile strength of the concrete matrix is exceeded, the material tensile resistance decreases considerably which results in a reduction of the equivalent bending stress up to 60 percent at a deflection of $\delta \approx 0.25$ mm. At 25 mm fibres only deflection softening behaviour is observed subsequently. Fig. 2 illustrates that the equivalent bending strength and also its variation increased by a more fluid fresh concrete consistency. 50 mm fibres show a slight increase of bending stress after the stress drop, which is followed by deflection softening. An increase in dispersion of bending strength combined with an increase of fresh concrete consistency was not observed by using 50 mm long steel fibres.

Tab. 2 summarizes the variation of the investigated flexural parameters of M1-4. The average bending strength $\sigma_m$, the standard deviation s, the 5%-fractile and the coefficient of variation $\nu$ are shown for a mid-span deflection of 0.5 mm (serviceability limit state) and 3.5 mm (ultimate limit state) for each of the four fibre reinforced concretes.

The statistical analysis points out the high variation in tensile behavior. With a deflection of 0.5 mm, the average bending strength is approximately independent of fibre length and consistency! At a deflection of 3.5 mm, flexural strength of 50 mm fibres is about twice as large as the one of 25 mm. The coefficient of variation is for 25 mm fibres and a consistency F6 about 1.5 times as larger than with a consistency F4. The variation coefficient for 50 mm fibres is approximately independent of the consistency and with 20 - 25 percent almost constant. The 5%-fractile values are inversely proportional to the scattering: the larger the spread, the smaller the fractile. As pointed out in Tab. 2 longer fibres lead to higher flexural strength at 0.5 and 3.5 mm and the variation coefficient is slightly affected by fibre length and fresh concrete consistency. Note that this conclusion is only valid as long the failure mechanism is primarily controlled by fibre pull-out.

Tab.2: Statistical analysis

| | M1 | M2 | M3 | M4 |
|---|---|---|---|---|
| **0.5 mm** | | | | |
| $\sigma_m$ [N/mm²] | 2.84 | 2.66 | 2.47 | 2.71 |
| s [N/mm²] | 0.46 | 0.65 | 0.64 | 0.56 |
| ν [−] | 16.1% | 24.4% | 25.8% | 20.6% |
| 5%-fractile [N/mm²] | 2.02 | 1.50 | 1.33 | 1.71 |
| **3.5 mm** | | | | |
| $\sigma_m$ [N/mm²] | 1.10 | 1.06 | 2.16 | 2.57 |
| s [N/mm²] | 0.26 | 0.37 | 0.55 | 0.58 |
| ν [−] | 24.0% | 34.8% | 25.4% | 22.6% |
| 5%-fractile [N/mm²] | 0.63 | 0.40 | 1.18 | 1.52 |

## 4. Fibre orientation and distribution of long beams

To investigate the influence of the manufacturing method on the fibre distribution and orientation, 3 beams with dimension l/w/h = 250 x 25 x 40 cm were cast. The beams differ in the fibre length (25 mm, 50 mm), and the manufacturing method due to the consistency (F4, F6). After the concrete's hardening, specimens were cut out of the concrete at specific positions, to determine the number of fibres and the orientation with the opto-analytic method [6].

### 4.1 Test setup and procedure

Two different manufacturing methods were used. The beam with concrete consistency F4 has been cast in layers, using a concrete bucket which was waved over the entire length. This method has been used for a beam with a fibre length of 25 mm. The beams with concrete consistency F6 have been cast from one end of the formwork (25mm, 50 mm). All beams were compacted by internal vibrators at specific positions. Fig. 2 shows the test setup. The concrete mix was the same as mentioned in Tab. 1 with a fibre content of 30 kg/m³. The mixing time was kept constant for all beams in order to ensure comparability.

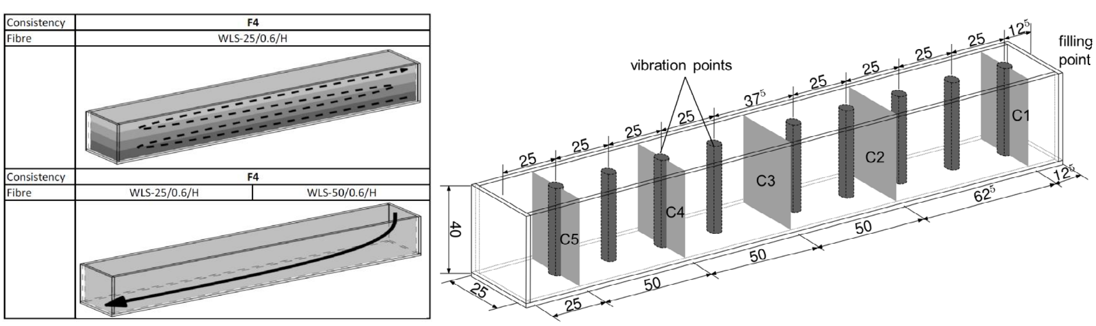


Fig. 4: Test setup for the long beams

For each bar 5 plates were cut out with a thickness of 5 cm. It can be seen on the cutting surfaces that no segregation of the concrete occurred in any beam. The concrete structure is closed and the coarse aggregate evenly distributed.

To reflect the number of fibres and their geometry clearly in the recording of the cut surfaces, the cut surfaces must be prepared after sawing, due to high thermal and mechanical stresses occurring during cutting. This stress increases with an increasing fibre content, resulting in a smearing of the fibre cross-section on the sectional area. By post-processing of the surfaces, the sectional area of the fibre, generally elliptically shaped, is restored. In addition, densely packed fibres, which were smeared due to the sawing into fibre clusters, are separated again. Fig. 5 shows a part of a cut surface with found and created ellipses.

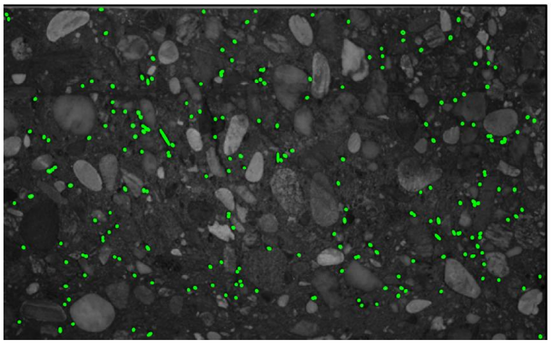


Fig. 5: Sectional area of found fibres and applied ellipses (image rotated by 90°)

## 4.2 Results & Discussion

The number of fibres and the fibre orientation for the various sections of all beams is given in Tab. 3. The fibre content $V_f$ in the section was calculated by Hilsdorf [8]:

$$V_f = \frac{N_f \cdot A_f}{h \cdot A_c} \tag{2}$$

Tab.3: Fibre orientation and number of fibres in the sections

| | | Fibre | Manu-facturing | C1 | C2 | C3 | C4 | C5 | average | coefficient of variation |
|---|---|---|---|---|---|---|---|---|---|---|
| Beam I | number of fibres $n_F$ | | | 821 | 708 | 700 | 666 | 802 | 739 | 9.2% |
| | fibre orientation $h_F$ | $l_f$= 25 mm Ø 0.6 mm | cast in layers | 0.57 | 0.57 | 0.58 | 0.62 | 0.62 | 0.59 | 4.2% |
| | fibre content [kg/m³] | | | 32.0 | 27.4 | 26.7 | 23.7 | 28.9 | 27.7 | 11.0% |
| Beam II | number of fibres $n_F$ | | | 827 | 917 | 972 | 696 | 644 | 811 | 17.3% |
| | fibre orientation $h_F$ | $l_f$= 25 mm Ø 0.6 mm | cast from one side | 0.48 | 0.69 | 0.65 | 0.61 | 0.57 | 0.60 | 13.5% |
| | fibre content [kg/m³] | | | 38.1 | 29.3 | 33.0 | 25.4 | 25.0 | 30.2 | 18.3% |
| Beam III | number of fibres $n_F$ | | | 752 | 793 | 735 | 793 | 695 | 754 | 5.5% |
| | fibre orientation $h_F$ | $l_f$= 50 mm Ø 0.6 mm | cast from one side | 0.56 | 0.52 | 0.60 | 0.55 | 0.53 | 0.55 | 5.7% |
| | fibre content [kg/m³] | | | 29.9 | 33.6 | 27.0 | 32.0 | 29.0 | 30.3 | 8.5% |

The analysis shows the variation in the fibre orientation and the number of fibres along the beams with different manufacturing methods. The fibre orientation is independent from the manufacturing method and fibre length for all beams with approximately 0.55 – 0.6 constant. These values are within the range of values determined by [3] and [4]. Along beam 1 the fibre number varies between 666 and 821, which corresponds to a variation of 10 percent. Beam 2, cast from one side, shows an even greater dispersion in the fibre distribution (644 – 972). Beam 3 with a fibre length of 50 mm shows the best results with a small dispersion in fibre distribution (695 – 793).

Furthermore it is interesting that the sections in which the internal vibrators were immersed (S1, S4, S5), no major differences were observed. The vibration gaps don't affect fibre orientation and distribution accordingly. The dispersion in the fibre content of [8] follows from the dispersion in the fibre distribution as well as the orientation. Based on a completely homogeneous fibre distribution, the number of fibres in the section must be greater with increasing orientation value. The present results don not confirm this statement. Therefore, the scattering is influenced by the uneven fibre distribution. The influence of the fibre orientation scattering on the post cracking tensile behavior is rather low. Slight changes in the angle at which the fibre crosses the crack are negligible due to the large plastic deformation of the steel fibres.

## 5. Cellar of FRC

A cellar of FRC was manufactured, which consists of a basement and two rising walls, to consider realistic conditions. The walls differ in the manufacturing method. The concrete was supplied by a mixing plant with a fresh concrete consistency of F6 and a compressive strength of C25/30 (25 mm fibre, 30 kg/m$^3$). Beams were cut out of the base plate and walls to determine the fibre distribution and orientation along them. For this purpose an opto-analytic method was used, as mentioned above (chapter 4.1). Bending tests were also performed with the beams, as described in chapter 3.1.

### 5.1 Test setup and procedure

The basement has dimension 3 m x 2 m and a thickness of 0.25 m and was cast from the center. The compaction was performed at pre-defined positions. 5 beams were cut out of the plate with a length of 70 cm and a width of 15 cm to determine the fibre orientation along their longitudinal side. Also 4-point-bending tests were performed with the beams. As shown in Fig. 6, 3 beams are orientated in flow direction, two in orthogonal direction.

Both walls have a length of 3 m, a height of 1.5 m and a thickness of 0.2 m. Wall 1 was filled in layers, wall 2 from one side. In wall 1, the concrete hose was taken in layers over the entire length. The compaction was performed at pre-defined positions as can be seen in Fig. 6. 6 beams were cut out of each wall with a length of 70 cm and a width of 15 cm to determine fibre orientation along their longitudinal side. Further 4-point-bending tests were performed with the beams.

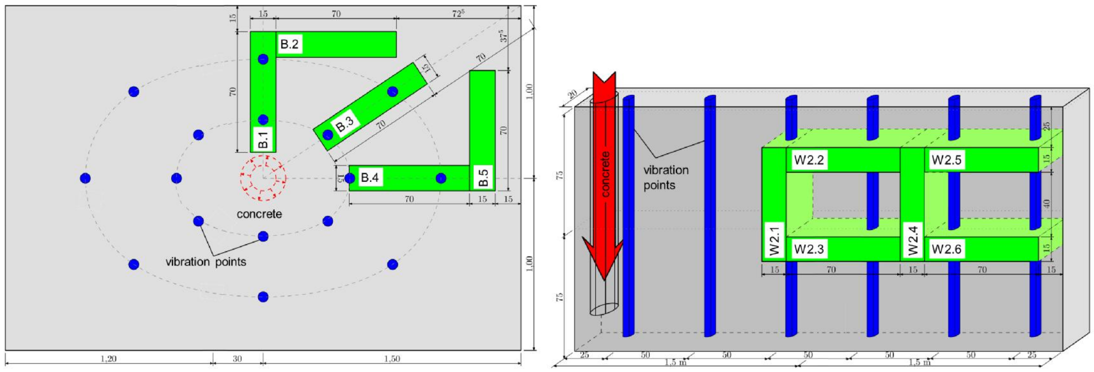


Fig. 6: Experimental setup of the basement (top view) and wall 2 and arrangements of the bending beams (equal for both walls)

## 5.2 Results & Discussion

The number of fibres and the fibre orientation for the cut out bending beams of the basement and the walls are given in Fig. 7 and Tab. 4. The bending test results are shown in Tab. 5 and Fig. 8.

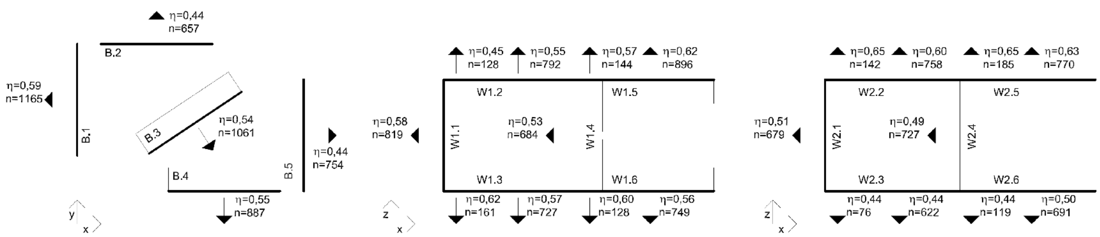


Fig. 7: Fibre orientation and number of fibres along the beams

Tab.4: Statistical analysis of the number of fibre and fibre orientation

| | | B.1 | B.2 | B.3 | B.4 | B.5 | W1/2.1 | W1/2.1 _top | W1/2.1 _bottom | W1/2.2 | W1/2.3 | W1/2.4 | W1/2.4 _top | W1/2.4 _bottom | W1/2.5 | W1/2.6 | **average** | **coefficient of variation** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basement | $\eta_{\text{Flow direction}}$ | | 0.44 | | | 0.44 | | | | | | | | | | | 0.44 | 0.4% |
| | $\eta_{\text{ortho flow dir}}$ | 0.59 | | 0.54 | 0.55 | | | | | | | | | | | | 0.56 | 4.9% |
| | **number of fibre** | 1165 | 657 | 1061 | 887 | 754 | | | | | | | | | | | 905 | 23.2% |
| Wall 1 | $\eta_x$ | | | | | | 0.58 | | | | | 0.53 | | | | | 0.55 | 6.0% |
| | $\eta_z$ | | | | | | | 0.45 | 0.62 | 0.55 | 0.57 | | 0.57 | 0.60 | 0.62 | 0.56 | 0.57 | 9.6% |
| | **number of fibre** | | | | | | 819 | 128 | 161 | 792 | 727 | 684 | 144 | 128 | 896 | 749 | 523 | |
| Wall 2 | $\eta_x$ | | | | | | 0.51 | | | | | 0.49 | | | | | 0.50 | 2.6% |
| | $\eta_z$ | | | | | | | 0.65 | 0.44 | 0.60 | 0.44 | | 0.65 | 0.44 | 0.63 | 0.50 | 0.54 | 18.2% |
| | **number of fibre** | | | | | | 679 | 142 | 76 | 758 | 622 | 727 | 185 | 119 | 770 | 691 | 477 | |

It can be seen, that the fibre orientation in the basement in the concrete flow direction (B.2, B.5) is lower than orthogonal to it (B.1, B.3, B.4). This result is surprising, as it has been always assumed that the fibres are aligned in the flow direction of the concrete [3], [4] and [9]. The bending test results correlate as followed: The higher the fibre orientation along the longside of the beam, the lower the flexural strength. Furthermore, it is apparent that the number of fibres with similar fibre orientation (B.1, B.3, B.4 and B.2, B.5) varies widely. The fractile of all 5 bending tests at a mid-span deflection of 0.5 and 3.5 mm results in a value of 0. For the determination of design values for basements, knowledge of the manufacturing method and direction is essential.

Tab.5: Statistical analysis of bending tests

| | basement | wall 1 | wall 2 |
|---|---|---|---|
| **0.5 mm** | | | |
| $\sigma_m$ [N/mm²] | 0.89 | 1.11 | 1.07 |
| s [N/mm²] | 0.58 | 0.31 | 0.35 |
| ν [–] | 64.5% | 28.3% | 32.8% |
| 5%-fractile [N/mm²] | 0.00 | 0.55 | 0.44 |
| **3.5 mm** | | | |
| $\sigma_m$ [N/mm²] | 0.22 | 0.44 | 0.40 |
| s [N/mm²] | 0.74 | 0.49 | 0.56 |
| ν [–] | 329.1% | 112.2% | 139.5% |
| 5%-fractile [N/mm²] | 0.00 | 0.00 | 0.00 |

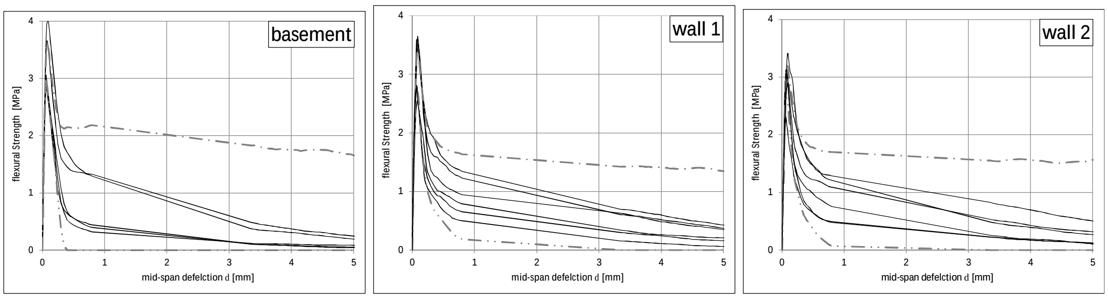


Fig. 8: Bending test results

In wall 1, the fibre orientation in vertical direction is approximately 0.5 to 0.6. The fibre orientation scatters with about 6 percent, and the number of fibres with 10 percent. Wall 2 has a greater dispersion and the fibres have a lower orientation mainly in the lower part. Further, the number of fibres in a section scatters in both walls in a large range. In wall 1 the fibres orientate three dimensional and not horizontal as expected. In the lower part of wall 2, the fibre orientation is more in horizontal direction. The results show that the fibres align better with manufacturing method 1. The large scatter in fibre distribution is reflected in the scattering of the bending test results again. It has to be mentioned that not all beams were located in the same direction in the component and the beam height was 25 cm. The fractile of all beams is at a mid-span deflection of 0.5 mm very low and 0 at 3.5 mm. To sum up, the manufacturing method of wall 1 is better, due to better fibre orientation.

## 6. Conclusion

The experiments illustrate the large scattering in post cracking tensile behavior of FRC. The dispersions which are achieved by small standard beams (l/w/h=70/15/15 cm) is in the region of 20 percent. This results in very small design values. Further the fibre orientation for horizontal cast beams is almost independent from the manufacturing method. However, the number of fibres in the cut surfaces shows a high dispersion and is different from specimen to specimen. Further, carefully executed vibration gaps don't lead to inhomogeneity in the fibre distribution. At the component level, the dispersion in fibre orientation and distribution is similar to the beams under laboratory conditions. Also in walls, a three dimensional fibre orientation is achieved with appropriate manufacturing methods. To compare the bending test results of the cellar with small sized beams, it must be mentioned that not all bars were equally aligned and tested at various axes. In comparison, the scale effect should be taken into account, due to a greater height of the beams of the basement and walls.

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