

# PRODUCTION AND TESTING OF BEAMS MADE OF STEEL FIBRE REINFORCED CONCRETE

WHITE PAPER



KRAMPE HAREX®

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The following table summarizes the most important parameters for the production and testing of beams made of steel fibre reinforced concrete:

Parameter	3-point bending test	4-point bending test
Standard/Guideline	EN 14651 [1]	DAfStb Guideline “Steel fibre reinforced concrete” [2]
Specimen dimensions	150 mm · 150 mm · [550 mm to 700 mm]	150 mm · 150 mm · 700 mm
Fibre length	≤ 60 mm	35 mm* to 60 mm* (Should be at least 1.5 times of the maximum grain size)
Maximum grain size	32 mm	16 mm for round grain 22 mm for crushed grain
Minimum number of beams	12 <sup>2)</sup> (14) <sup>3)</sup>	At least 6 (7) <sup>3)</sup>
Notch	Width: 5 mm, beam height at notch 125 ±1 mm	–
Test	Crack opening (CMOD) or deflection	Deflection
Span length	500 mm	600 mm
Test speed	CMOD up to 0.1 mm: 0.05 mm/min (recording with ≥ 5 Hz) CMOD greater than 0.1 mm: 0.2 mm/min (recording with ≥ 1 Hz)	Deflection up to 0.75 mm: 0.10 mm/min Deflection from 0.75 mm: 0.30 mm/min
Other	The test shall be terminated when the value of CMOD is not less than 4 mm.	Loads and deflections shall be recorded up to 3.5 mm in 0.01 mm increments.
Evaluation	Crack opening (deflection): f <sub>R1</sub> (CMOD = 0.5 mm (0.47 mm)) – serviceability limit state (SLS) f <sub>R2</sub> (CMOD = 1.5 mm (0.47 mm)) f <sub>R3</sub> (CMOD = 2.5 mm (2.17 mm)) – ultimate limit state (ULS) f <sub>R4</sub> (CMOD = 3.5 mm (3.02 mm))	Performance classes: L1 (0.5 mm deflection) – serviceability limit state (SLS) L2 (3.5 mm deflection) – ultimate limit state (ULS)

<sup>1)</sup> In case of a higher nominal value of the maximum grain size, separate considerations are required regarding the dimensions of the specimens

<sup>2)</sup> According to EN 14845-2 [3].

<sup>3)</sup> Recommendation based on the experience of KrampeHarex

\* Usual value according to booklet 614 of the DAfStb Commentary on the DAfStb Guideline “Steel Fibre Reinforced Concrete” [4].

Within the scope of this white paper, the explanations of various standards, recommendations, codes of practice and guidelines for beam tests with a focus on the EN 14651 and the guideline “Steel Fibre Reinforced Concrete” of the German Committee for Reinforced Concrete (DAfStb). It is intended to provide an overview of the rules to be followed and the various steps to be considered in the production and testing of beams made of steel fibre reinforced concrete.

The performance of steel fibres according to EN 14889-1 [5] in concrete is determined by the residual (post-cracking) flexural tensile strength. The determination of the

**The performance of steel fibres according to EN 14889-1 in concrete is determined by the residual (post-cracking) flexural strength. The determination of the flexural strength of concrete with steel fibres is carried out on separately manufactured samples.**

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Internationally, the 3-point bending test according to EN 14651 [1] is predominantly used. In Germany, the 4-point bending test according to the DAfStb guideline “Steel Fiber Reinforced Concrete” [2] is (still) used, which is also partly used in other European countries.

The 3-point bending test according to EN 14651 [1] is a test specifically developed to characterize steel fibre reinforced concrete and to derive design parameters. This test method is intended for steel fibres with a maximum length of 60 mm and a maximum grain size of 32 mm. The application of the method can also be used for a combination of steel fibres and for a combination of steel fibres with other fibres. Nevertheless, this white paper deals exclusively with the production and testing of beams made of steel fibre reinforced concrete.

The advantage of this test according to EN 14651 [1] is that the strength is related to specific CMODs and the strength indices can be used directly in the design for the corresponding limit state. The tensile behavior of steel fibre reinforced concrete is evaluated based on the residual flexural tensile strength, which is based on the load-crack opening curve or the load-deflection curve obtained by applying a center load to a simply supported notched beam.

Test results are expressed in Limit of Proportionality (LOP) and residual flexural tensile strength. Classification of the results of the 3-point bending test according to EN 14651 [1] is possible according to FIB MODEL CODE 2010 [6], considering RILEM TC 162-TDF: “Test and design methods for steel fibre reinforced concrete” [7].

The “Steel fibre reinforced concrete” guideline of the DAfStb [2], which describes the 4-point bending test, is a document introduced by the building authorities in Germany that regulates the properties and applications of the building material “steel fibre reinforced concrete” that are not covered by DIN EN 1992-1-1 [8] in conjunction with

DIN EN 1992-1-1/NA [9] (Eurocode 2), DIN EN 206-1 [10] in conjunction with DIN 1045-2 [11] and DIN EN 13670 [12] in conjunction with DIN 1045-3 [13] or the “Water impermeable structures made of concrete” guidelines [14] the DAfStb guidelines “Concrete construction for handling water-polluting substances” [14] or “Water-impermeable structures made of concrete” [15].

The DAfStb guidelines “Concrete Structures as Barrier against Penetration of Water-Hazardous Substances” [14] and “Water Impermeable Structures made of Concrete (WU Guideline) [15] already include the use of steel fibre reinforced concrete. Based on the DAfStb guideline “Steel fibre reinforced concrete” [2], it is possible to classify

“The explanations in this White Paper mainly refer to DIN EN 14651 as well as the guideline “Steel Fibre Reinforced Concrete” in combination with booklet 614 “Explanations of the Steel Fibre Reinforced Concrete Guideline”.

steel fibre reinforced concrete into performance classes based on the post-cracking bending tensile strength determined in the 4-point bending test. Performance class L1, which is used for small deformations, represents the serviceability limit state (SLS), and performance class L2 for larger deformations represents the ultimate limit state (ULS).

The explanations in this white paper mainly refer to DIN EN 14651 [1] and the guideline “Steel Fibre Reinforced Concrete” [2] in combination with booklet 614 “Explanations of the Steel Fibre Reinforced Concrete Guideline” [4].

## 3.1 Specimens

The specimens (beams) must have a cross-section of 150 mm · 150 mm for both the 3-point and the 4-point bending test. The length of the beams for the 3-point bending test may be between 550 mm and 700 mm. In practice, a length of 550 mm is often used. In the 4-point bending test, a length of 700 mm is prescribed.

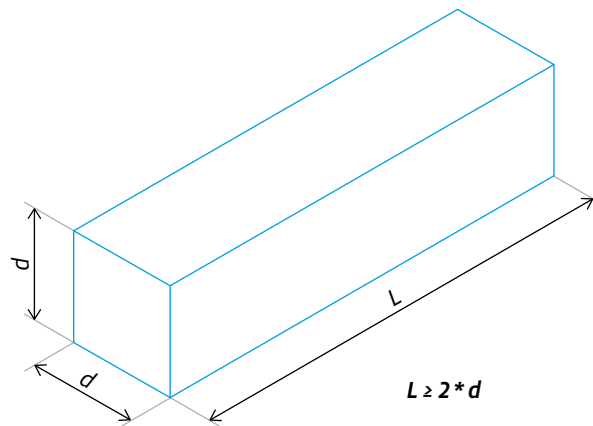


Figure 1: Nominal dimensions of prism (beam) based on DIN EN 12390-1 [16]

According to DIN EN 12390-1 [16], the following tolerances must be observed for samples to be manufactured:

- For moulded faces, a maximum permissible deviation of 1 % of the of the nominal dimension  $d$  (see Figure 1).
- The limit value of the permissible deviation of the fill-in side from the moulded base surface is 1.5 % of the nominal dimension.
- The squareness of the side surfaces in relation to the base surface is limited to a maximum of 0.5 mm.
- The surfaces in contact with the supports during the bending test must not deviate by more than 0.3 mm in straightness.

The tolerances for squareness and height are shown graphically in Figure 2.

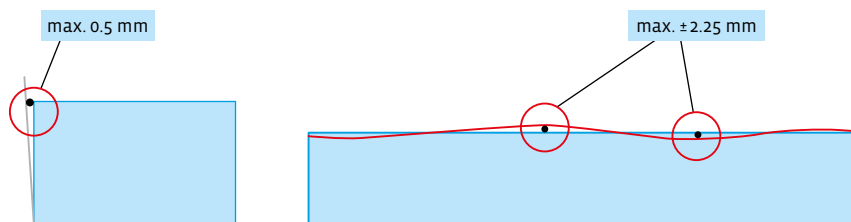


Figure 2: Tolerances for squareness (top) and tolerances for height (fill-in side to moulded base surface) according to DIN EN 12390-1 [16].

### 3.1.1 3-point bending test

For the 3-point bending test according to EN 14651 [1], twelve notched beams shall be tested according to EN 14845-2 [3]. The fibres shall be placed in a reference concrete according to EN 14845-1 [17].

For the 3-point bending test according to EN 14651, twelve notched beams are to be tested in accordance with EN 14845-2.

For the beams with dimensions of 150 mm · 150 mm · 550 (up to 700 mm), the maximum grain size of the aggregates may be up to 32 mm and/or the length of the steel fibres may not exceed 60 mm.

### 3.1.2 4-point bending test

Testing of the post-cracking bending tensile strength according to Annex O for classification of the concrete into a performance class and for checking the performance class should be carried out with a buffer, but must not be carried out with more than the minimum value of the steel fibre content  $m_{f,min}$ . The correct application of the buffer is described in the leaflet “Dosage of steel fibres for the production of specimens for the initial test to determine the performance class” [18].

At least 6 beams are used for the 4-point bending test. The dimensions as well as tolerances are described in detail in Section 3.1. The maximum grain size of the aggregates used for the dimensions of the beams of 150 mm · 150 mm must not

At least 6 beams are used for the 4-point bending test.

exceed 16 mm for a round grain and 22 mm for a crushed grain. If a higher nominal value of the maximum grain is to be tested, separate considerations must be made regarding the dimensions of the specimens. The minimum length of the steel fibres should be at least

1.5 times of the existing maximum grain size. For production (cf. Section 3.3.2), the specifications of DIN EN 12390-2 [20] must be considered. The concrete composition including type and quantity of fibres is determined by the manufacturer of the steel fibre reinforced concrete.

## 3.2 Concrete production in ready-mix concrete plant

For the production in the ready-mix concrete plant, a time horizon of approx. 2 hours must be planned. As in the laboratory tests, a suitable concrete formulation for steel fibres must be used.

For the production of steel fibre reinforced concrete, a concrete mixing truck shall be provided with a clean drum for a period of about 1.5 hours. No water and/or residues of concrete admixtures must be present in the drum of the concrete mixing truck. In

addition, it should be ensured that no air-entrained concrete was delivered on the concreting day of the production of the specimens with the concrete mixing truck to be used.

The fibre is added via the concrete mixing truck and not via the mixing plant - exception: A (fully) automatic dosing plant for fibres is available. The mixing time should be at least 5 minutes to ensure homogeneous distribution of the fibres.

For filling the beam moulds (cf. Section 3.4), it must be ensured that the vibrating table is standing straight aligned on a hard base.

The concrete should be filled from the concrete mixing truck into a wheelbarrow and removed from the edge using a suitable shovel (cf. Section 3.4). Poking should be avoided in order not to influence the fibre distribution.

### 3.3 Concrete production in laboratory

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#### 3.3.1 3-point bending test

A suitable (disc) mixer is to be used for mixing the concrete. Coarse aggregates, sand and cement are added to the mixer in this order and mixed for 60 seconds. Then the mixing water is added and the further mixing time is 60 seconds. Finally, the fibres are added. The mixing time is 270 seconds to ensure that all fibres are separated and homogeneously distributed. Finally, a visual inspection of the distribution of the Fibre should be made.

#### 3.3.2 4-point bending test

For homogeneous fibre distribution, the following mixing sequence is recommended according to [2] to ensure that a homogeneous fibre distribution is achieved:

- Add aggregates to the compulsory mixer and mix for at least 30 seconds.
- Then add cement and concrete additive and mix for another 30 seconds.
- Water is added as well as liquefying concrete admixtures during a minimum mixing time of 30 seconds.



- To ensure uniform addition of loose steel fibres, a trough should be used to prevent formation of balls during a further minimum mixing time of 60 seconds. Subsequently, a mixing time of at least 90 seconds should be observed. It is important to check that all fibres are homogeneously distributed. In the case of bonded fibres, additional care should be taken to ensure that the fibres are singled. Otherwise, the mixing time must be extended.

In the case of a mixer with fixed mixer blades, regular lifting is recommended to avoid fibre accumulation. Visual inspection of the mixing process is always required.

### 3.4 Filling and compacting the beam moulds

#### 3.4.1 General information

It must be ensured that the labeling of the beams is clear and permanent until the test.

The moulds shall be checked before filling to ensure that form releasing agent has been applied and that all existing bolts are tight.

#### 3.4.2 3-point bending test

Unless otherwise specified, the specimens shall be manufactured and cured in accordance with EN 12350-1 [19] and EN 12390-2 [20].

The procedure of filling into the moulds is shown in Figure 3. The size of portion 1 should be twice that of portion 2 or 3. It is important to use a wide and large shovel (not a small shovel like a trowel). The moulds shall be filled to approximately 90 % of the height of the specimen before compaction. During compaction, the concrete shall be backfilled and stripped. The moulds shall be backfilled and leveled with an external vibrator during compaction. Compaction/vibration time depends on the consistency of the steel fibre reinforced concrete. In the case of very stiff concrete, equipment with two motors that can provide all the energy as vertical energy is advantageous (high-frequency vibrating table with 6000 – 9000 rpm). The usable area should be at least 400 mm - 600 mm. In the case of self-compacting concrete with steel fibres, the mould is filled and removed without compaction. The sequence of filling is analogous to the 4-point bending test (cf. Figure 3, Section 3.4.3).

### 3.4.3 4-point bending test

When filling the beam mould, it must be ensured that the steel fibre reinforced concrete is filled quickly and that no unusual fibre orientations occur. In order to influence the fibre distribution as little as possible, a flat sampling shovel should be used for filling. According to [4], the filling sequence shown in Figure 3 – starting in the center of the beam mould – is recommended.

When filling the beam mould, it must be ensured that the steel fibre reinforced concrete is filled quickly and that no unusual fibre orientations occur.

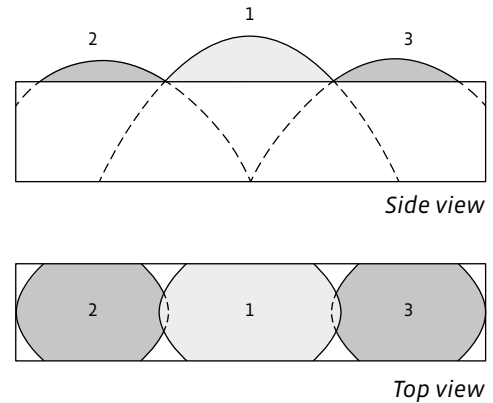


Figure 3: Filling sequence of the beam mould for the 4-point bending tests [21] from [4].

To compact the steel fibre reinforced concrete in the beam mould, only the use of an external vibrator - vibrating table of sufficient size - is allowed. For consistency classes F3 and F4, a vibration time of 30 seconds is usually sufficient to ensure complete compaction of the concrete. If concretes of consistency class F6 are used, manual compaction by poking is allowed.

## 3.5 Post-treatment curing and storage

### 3.5.1 3-point bending test

The specimens are cured in accordance with EN 12390-2 [20]. They should remain in the moulds for at least 16 hours, but not longer than 3 days, protected from impact, vibration and drying at a temperature of  $20 \pm 5$  °C.

After removal from the mould, the specimens are rotated 90° and then sawed across the width of the specimen at midspan (the notch is sawed on the right or left side of the specimen, not on the top or bottom). The width of the notch must not exceed 5 mm (cf. Section 4.2.1, Figure 4, bottom left).

The specimens shall be allowed to cure at least 3 days after sawing until 3 hours before testing under water at a temperature of  $20 \pm 2$  °C or in a climatic chamber at  $20 \pm 2$  °C and a relative humidity of at least 95 %. Regular checks should be made to ensure that the surfaces of the specimens in the chamber are consistently moist.

Loss of moisture must be avoided during transport (to the laboratory). Specimens should be transported in sealed plastic bags containing water.

### 3.5.2 4-point bending test

“After stripping, the specimens must be conditioned at about 100 % humidity. Optionally, storage can be in foil, in water or in a climatic room with a relative humidity  $\geq 95$  %.”

After completion of the compaction process, the open filling side of the mould must be covered with foil and the specimens must be stored in the climatic room. Usually, the moulds covered with the foil are stored for 2 days in the climatic room. If early strength cements are used, storage for 24 hours is sufficient. After stripping the moulds, the specimens must be conditioned at about 100 %

humidity. They can be stored in foil, in water or in a climatic room with a relative humidity  $\geq 95$  %. The specimens must be stored at  $(20 \pm 5)$  °C until the specified test date - usually 28 days. If the specimens are stored in foil, it must be ensured that they are sealed, e.g., with adhesive tape, in order to avoid water release.

## 4.1 General information

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Before starting the tests, it should be known which laboratory and method will be used to provide additional information and advice and to better understand the test results.

## 4.2 Preparation of the specimens

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### 4.2.1 3-point bending test

The test should be performed after 28 days.

There are two methods:

- In the first method, the opening travel of the crack (or notch) is measured by placing a displacement transducer along the longitudinal axis at the center of the width of the specimen inside the notch so that the distance  $y$  between the bottom of the specimen and the line at which measurement is made is 5 mm or less (see Figure 4, top).
- In the second method, deflection is measured by attaching a displacement transducer to the bottom of the specimen, which should be attached to a rigid frame at the center of the component height on the specimen above the supports. One side of the frame should be attached to the specimen with a sliding fixture, the other with a tilting fixture. Since the displacement transducer is to measure deflection, a thin plate can be attached to one end at mid-width over the notch opening at the measurement point (see Figure 4, bottom).

# 4. TESTING

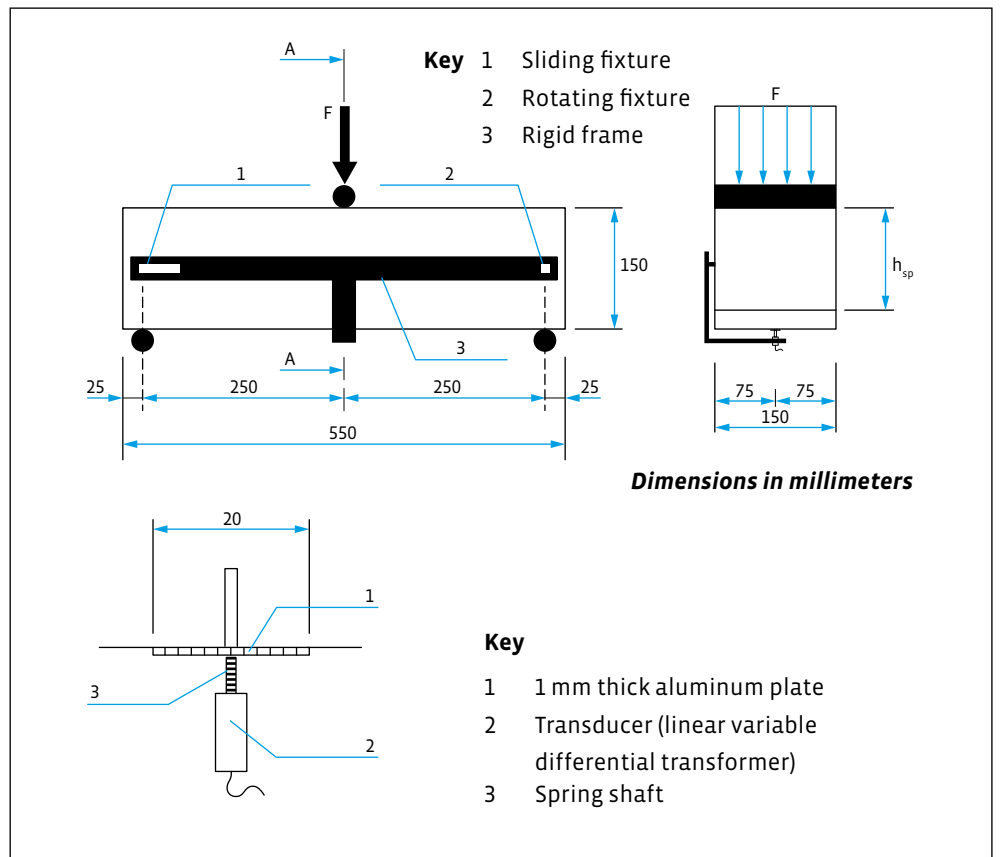
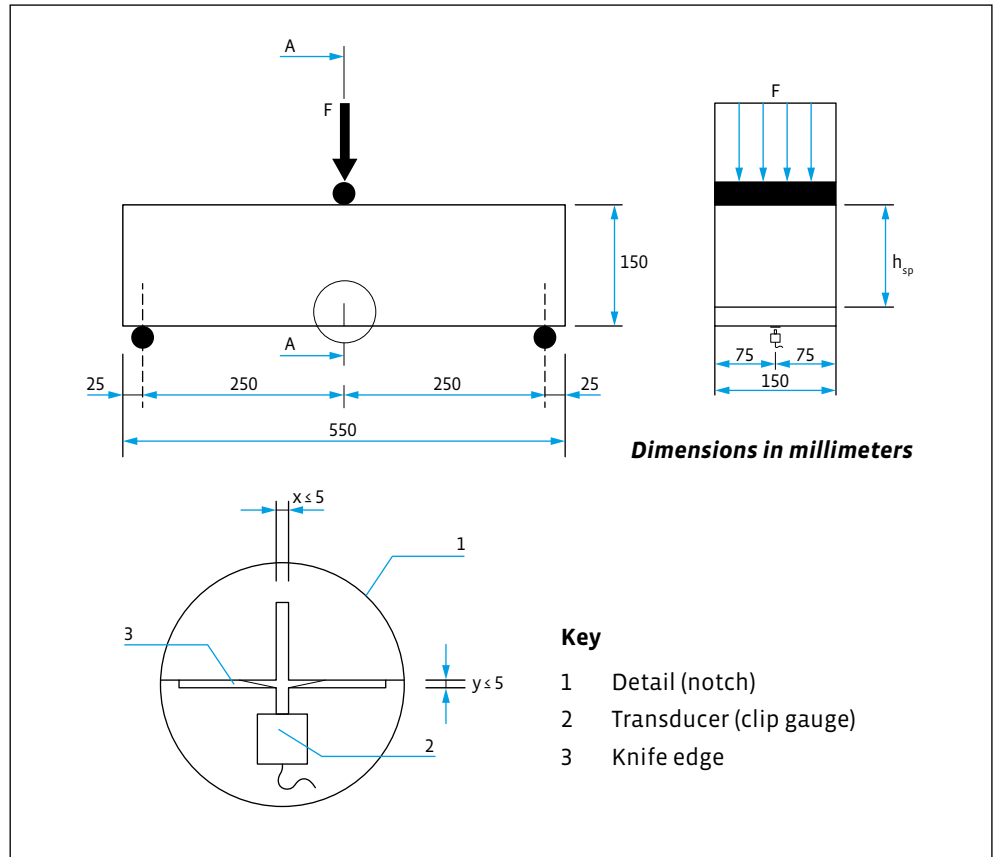


Figure 4: Typical arrangement for measuring CMOD (top) and deflection (bottom) [1]

**4.2.2 4-point bending test**

The specimens are tested at 28 days of age unless otherwise specified. For special applications, it may be necessary to perform the test later than 28 days.

The specimen may be removed from the foil, water or climatic chamber a maximum of 24 hours before testing the bending strength and post-cracking behavior. The specifications of DIN EN 12390-5:2009-07 [22], sections 5 and 6.1, must be observed. The fill-in side of the beam is always a side surface of the specimen to ensure that only moulded faces are in contact with the support rollers.

In addition, the bulk density of the beam must be determined according to DIN EN 12390-7 [23] as part of the test preparation.

Subsequently, the fixtures for the measured value acquisition are attached to the specimen. Figure 5 shows the measuring fixture.

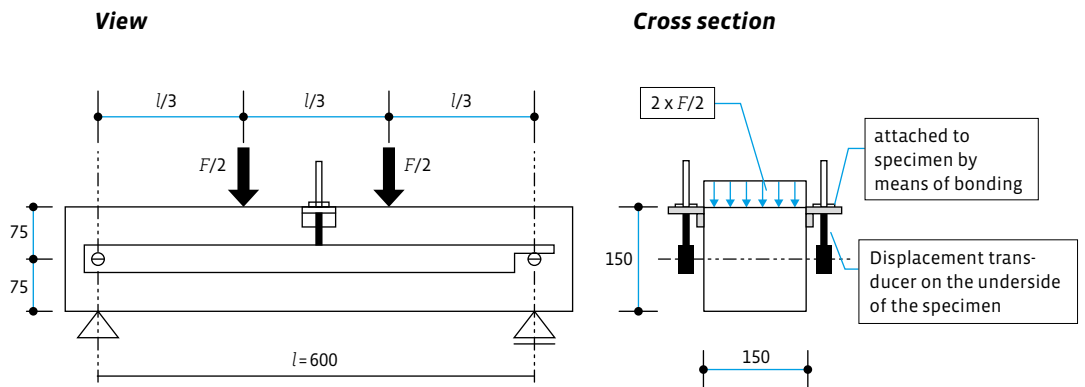


Figure 5: Measuring device for determining the post-cracking tensile strengths (dimensions in mm) for the 4-point bending test [2].

**4.3 Testing devices**

**4.3.1 General information**

The specimen shall be mounted in the center of the test machine with the longitudinal axis of the specimen perpendicular to the longitudinal axis of the upper and lower rollers.

All load applying surfaces shall be wiped clean and any loose debris or other foreign material shall be removed from the surfaces of the specimen in contact with the rollers.

Prior to performing each bending test, the average support span of the specimen shall be determined from two measurements of the distance between the axes of the support rollers on both sides of the specimen, using a ruler to the nearest 1 mm.

The load shall not be applied until the loading roller and the support rollers are in uniform contact with the specimen.

#### 4.3.2 3-point bending test

The stiffness of the loading frame is the critical factor in obtaining unbiased results. This stiffness is essential to detect the first crack in the deformation curve

**The stiffness of the loading frame is the critical factor in obtaining unbiased results.**

and ultimately to describe the resistance of the components. The testing machine must comply with Class 1 according to EN 12390-4 [24] and allow for displacement-controlled testing (steady change of displacement (CMOD or deflection)).

With weaker frame designs, the first crack will be mapped incorrectly, invalidating the test results.

The stiffness of the test frame should be at least 2.8 MN/mm and the control speed at least 5 kHz.

The device for load application from the testing machine to the specimen, must consist of two support rollers and one load application roller. All rollers must be made of steel and have a circular cross-section with a diameter of at least 30 mm ± 1 mm. They shall be at least 10 mm longer than the width of the specimen. Two of the rollers, including the upper one, shall be free to rotate about their longitudinal axis and shall be tiltable in the plane perpendicular to the longitudinal axis of the specimen. The span length must be 500 mm.

#### 4.3.3 4-point bending test

The 4-point bending test must be carried out on a displacement-controlled testing machine (quality class 1 to DIN 51220 [25]) with sufficiently high machine stiffness, sufficiently short reaction time and sufficiently high measuring frequency to ensure that an uncontrolled drop in the load-deflection curve after exceeding the crack load is avoided. If a testing machine or testing device is used that is too soft, an overestimation of the post-cracking bending tensile strengths will occur. This is particularly the case for the 0.5 mm deformation (L1). Due to the comparatively large jump between the deflection points at maximum load and the beginning of the post-cracking bending tensile range, the resulting loads are overestimated by up to two performance classes.

The span length  $l$  must be 600 mm. The restraint-free support and load application must be ensured, since otherwise a compression bow can form, which also leads to an overestimation of the performance class. For this purpose, at least one support must ensure the free movement of the specimen in the horizontal direction. The same applies to the two load application points.

## 4.4

**Performance of the tests**

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**4.4.1 3-point bending test**

When performing the test with control over the crack opening (CMOD), the machine shall be controlled with a constant speed of the crack opening (CMOD) of 0.05 mm/min up to a crack opening CMOD of 0.1 mm. From CMOD of 0.1 mm, the CMOD may increase at a speed of 0.2 mm/min.

The frequency for recording the load and the associated CMOD shall be at a frequency of not less than 5 Hz within the first two minutes of the test and not less than 1 Hz thereafter.

The test shall be performed at least to a value of CMOD of 4 mm and shall not be terminated before that time.

If the lowest value of the load between  $CMOD_{F_L}$  and  $CMOD = 0.5$  mm is less than 30 % of the load associated with the value of  $CMOD = 0.5$  mm, the test procedure shall be examined for discontinuities.

If the control of the speed increase of the testing machine is carried out via the deflection, the test procedure described for the crack opening (CMOD) shall be applied. It shall be ensured that the parameters related to CMOD in Table 1, Section 5.1 are converted to parameters related to deflection.

If cracks occur outside the indentation during the test, the tests shall be classified as invalid and discarded.

**4.4.2 4-point bending test**

The speed of deflection shall be limited to 0.10 mm/min during the test up to a center deflection of 0.75 mm. Control of the testing machine via the piston travel is prohibited. If the deflection is greater than 0.75 mm, a gradual increase in the deflection rate



to a maximum of 0.30 mm/min is permitted. The loads and associated deflections shall be measured and graphically recorded up to a specimen deflection of 3.5 mm in 0.01 mm increments.

If the initial crack formation occurs at a deflection significantly greater than approx. 0.1 mm, the test arrangement must be checked. The cause may be, for example, incorrectly mounted displacement transducers or the measurement of deflection with externally placed optical devices. As a result, deformations at the supports, for example, are incorrectly evaluated as deflections. In this case, the position of the displacement transducers must be checked. For further possible sources of error during the execution of the test and their handling during the evaluation, please refer to chapters 3.2 and 3.4 in [26].

## 5.1 3-point bending test

In the evaluation according to 14651 [1], the Limit of Proportionality  $f_{ct,L}^f$  (LOP) is determined:

$$f_{ct,L}^f = \frac{3 \cdot F_L \cdot l}{2 \cdot b \cdot h_{sp}^2} \quad (1)$$

$f_{ct,L}^f$  Limit of Proportionality [N/mm<sup>2</sup>]

$F_L$  Load belonging to the Limit of Proportionality [N]

$l$  Span length [mm]

$b$  Width of the specimen

$h_{sp}$  Distance between the tip of the indentation and the top of the specimen [mm]

To determine the load  $F_L$  belonging to the Limit of Proportionality, a line is drawn parallel to the load axis of the load CMOD or the load deflection curve at a distance of 0.05 mm.  $F_L$  represents the maximum load in the interval from 0 to 0.05 mm and is calculated to the nearest 0.1 N/mm<sup>2</sup>.

The following Figure 6 shows examples of the correct determination of  $F_L$ .

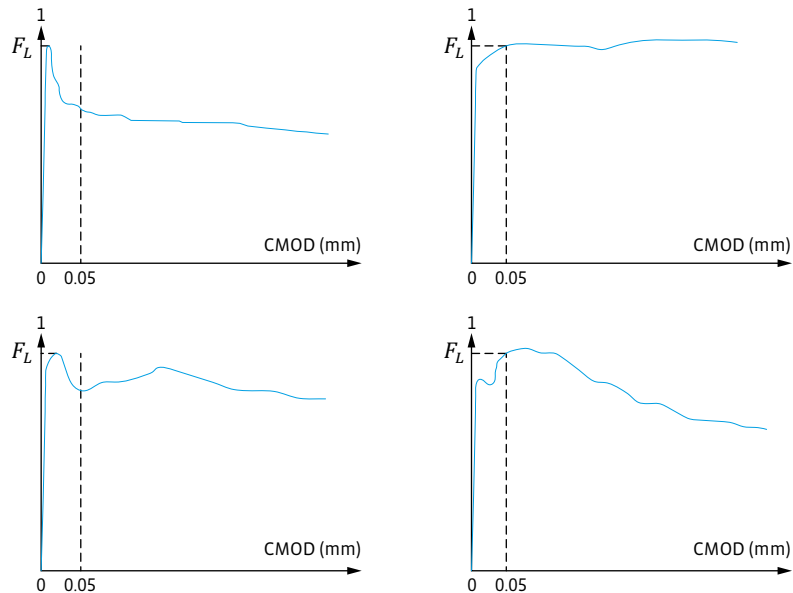


Figure 6: Load CMOD diagrams and  $F_L$  [1]

In addition to the Limit of Proportionality  $f_{ct,L}^f$ , the residual flexural tensile strength  $f_{R,j}$  (see Figure 7) is also determined rounded to 0.1 N/mm<sup>2</sup>:

$$f_{R,j} = \frac{3 \cdot F_j \cdot l}{2 \cdot b \cdot h_{sp}^2} \quad (2)$$

$f_{R,j}$  Residual flexural tensile strength [N/mm<sup>2</sup>] belonging to CMOD = CMOD<sub>j</sub> or  $\delta = \delta_j$  (j = 1, 2, 3, 4)

$F_j$  Load [N] associated with CMOD = CMOD<sub>j</sub> oder  $\delta = \delta_j$  (j = 1, 2, 3, 4) (cf. Figure 7)

$l$  Span length [mm]

$b$  Width of the specimen [mm]

$h_{sp}$  Distance between tip of indentation and top of specimen [mm]

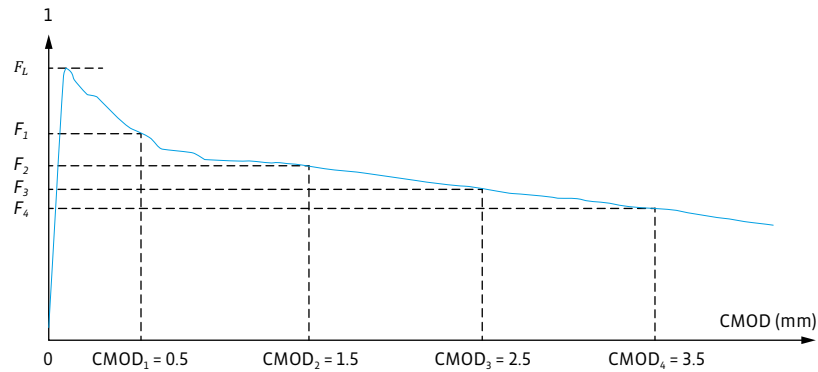


Figure 7: Load-CMOD diagrams and  $F_j$  (j = 1, 2, 3, 4) [1]

The ratio of CMOD and the deflection can be calculated according to the following equation:

$$\delta = 0.85 \cdot \text{CMOD} + 0,04 \quad (3)$$

$\delta$ : deflection [mm]

CMOD: value of CMOD [mm] when the distance  $y$  between the bottom of the specimen and the line in which is measured is equal to 0.

If the distance  $y$  is measured at the bottom of the specimen, the value for CMOD can be estimated from the measured CMOD<sub>y</sub> by the following equation:

$$\text{CMOD} = \text{CMOD}_y \cdot \frac{h}{h+y} \quad (4)$$

$h$ : Total height of the specimen

To translate the load-CMOD diagram of Figures 6 and 7 into load-deflection diagrams, it is recommended to shift the CMOD axis using the  $\delta$ -values of Table 1.

*Table 1: Relationship between CMOD and  $\delta$  [1].*

CMOD [mm]	$\delta$ [mm]
0.05	0.08
0.1	0.13
0.2	0.21
0.5	0.47
1.5	1.32
2.5	2.17
3.5	3.02
4.0	3.44

According to the explanations in [7], the conversion relationship between “characteristic” residual flexural tensile strength  $f_{R,j}$  and “mean” residual flexural tensile strength  $f_{R,jk}$  can be represented according to the following formula:

$$f_{R,jk} = f_{Rm,j} - k_x \cdot s_p \quad (5)$$

$f_{R,jk}$ : Characteristic residual flexural tensile strength [N/mm<sup>2</sup>] associated with CMOD = CMOD<sub>j</sub> oder  $\delta = \delta_j$  (j = 1, 2, 3, 4)

$f_{Rm,j}$ : Mean residual flexural tensile strength [N/mm<sup>2</sup>] associated with CMOD = CMOD<sub>j</sub> oder  $\delta = \delta_j$  (j = 1, 2, 3, 4)

$s_p$ : Standard deviation [N/mm<sup>2</sup>]:

$$s_p = \sqrt{\frac{\sum (f_{Rm,j} - f_{R,j})^2}{(n - 1)}}$$

n: Number of specimens

$k_x$ : Fractile factor as a function of the number of specimens (see Table 2)

In Table 2,  $k_{x\text{unknown}}$  means that the coefficient of variation of the population is unknown - instead of the standard deviation of the population, the standard deviation of the specimen control is used.

Table 2: Fractile factor  $k_x$  [7]

n	1	2	3	4	5	6	8	10	20	30	$\infty$
$k_{x\text{known}}$	2.31	2.01	1.89	1.83	1.80	1.77	1.74	1.72	1.68	1.67	1.64
$k_{x\text{unknown}}$	-	-	3.37	2.63	2.33	2.18	2.00	1.92	1.76	1.73	1.64

**Classification of the results of the 3-point bending test (EN 14651) according to FIB MODEL CODE 2010**

5.2

The test procedure according to EN 14651 [1] was adopted from the Model Code 2010 [6].

The post-cracking flexural tensile strength is classified first by the strength interval of  $f_{R1k}$  and second by the  $f_{R3k}/f_{R1k}$  ratio. The number represents the  $f_{R1k}$  class, while the letter represents the ratio of  $f_{R3k}/f_{R1k}$ .

The characteristic post-cracking residual flexural tensile strengths, which are of central importance according to the FIB Model Code, are:

- $f_{R1k}$  (CMOD = 0.5 mm) for the serviceability limit state design (SLS)
- $f_{R3k}$  (CMOD = 2.5 mm) for the verification of the ultimate limit state (ULS)

The post-cracking flexural tensile strength is classified first by the strength interval of  $f_{R1k}$  and second by the  $f_{R3k}/f_{R1k}$  ratio. The number represents the  $f_{R1k}$  class, while the letter represents the  $f_{R3k}/f_{R1k}$  ratio.

The strength interval for  $f_{R1k}$  is defined as follows:

- 1.0; 1.5; 2.0; 2.5; 3.0; 4.0; 5.0; 6.0; 7.0; 8.0 [N/mm<sup>2</sup>].

The  $f_{R3k}/f_{R1k}$  ratio is represented by the letters a, b, c, d and e corresponding to the following ranges:

- “a” for  $0.5 \leq f_{R3k}/f_{R1k} \leq 0.7$
- “b” for  $0.7 \leq f_{R3k}/f_{R1k} \leq 0.9$
- “c” for  $0.9 \leq f_{R3k}/f_{R1k} \leq 1.1$
- “d” for  $1.1 \leq f_{R3k}/f_{R1k} \leq 1.3$
- “e” for  $1.3 \leq f_{R3k}/f_{R1k}$

Example: “Steel fibre reinforced concrete C50/60 - 5.0c”.

- Characteristic compressive strength on cylinder ( $f_{ck,cyl}$ ) = 50 N/mm<sup>2</sup> or on tube ( $f_{ck,cube}$ ) = 60 N/mm<sup>2</sup>
- Residual flexural tensile strength at CMOD = 0.5 mm,  $f_{R1k}$  = 5,0 N/mm<sup>2</sup>
- Residual flexural tensile strength at CMOD = 2.5 mm,  $f_{R3k}$  = 4.5 (0.9 \*  $f_{R1k}$ ) to 5.5 N/mm<sup>2</sup> (0.9 \*  $f_{R1k}$ )
- Note that  $f_{R1k}$  is in a range of 5.0 and 5.9 N/mm<sup>2</sup>, so that also  $f_{R3k}$  can vary from 4.5 to 5.5 N/mm<sup>2</sup> for  $f_{R1k}$  = 5.0 N/mm<sup>2</sup> and up to 5.31 to 6.49 N/mm<sup>2</sup> for  $f_{R1k}$  = 5.9 N/mm<sup>2</sup> can vary
- All strength values are always characteristic values after statistical evaluation.

The tested steel fibre reinforced concrete may only be used if the following two requirements are met:

- $f_{R3k}/f_{LK} > 0.4$  and
- $f_{R3k}/f_{R1k} > 0.5$

Here,  $f_{LK}$  is the characteristic value of the Limit of Proportionality (LOP, cf. Sections 2 and 5.1), which corresponds to the maximum load to be applied (or to the highest value in the interval 0 – 0.05 mm) determined in the beam tests according to EN 14651 [1].

### Classification of the results of the 3-point bending test (EN 14651) according to DIN EN 14845-2

5.3

According to DIN EN 14845-2 [3], the amount of fibres shall be determined with which the following two requirements are met:

- Residual flexural tensile strength at a crack widening (CMOD) of 0.5 mm (corresponding to central deflection of 0.47 mm):  $\geq 1.5$  MPa
- Residual flexural tensile strength at a crack widening (CMOD) of 3.5 mm (corresponding to central deflection of 3.02 mm):  $\geq 1.0$  MPa

To determine the average performance of the 12 beams, outliers should be detected using Grubb’s test described in ISO 5725-2:1994 [27] for a probability of 5 %.

All non-representative results that fall outside the limit should be excluded.

5.4

**Performance classes according to the Steel Fibre Reinforced Concrete Guideline of the German Committee for Reinforced Concrete - 4-point bending test**

In the 4-point bending test according to [2], as shown in Figure 8, at the deflection points  $L1 = 0.5$  mm (performance class 1 (L1) - serviceability limit state) and  $\delta L2 = 3.5$  mm (performance class 2 (L2) - ultimate limit state), the post-cracking bending tensile strengths are determined from the load-deflection curve of the test.

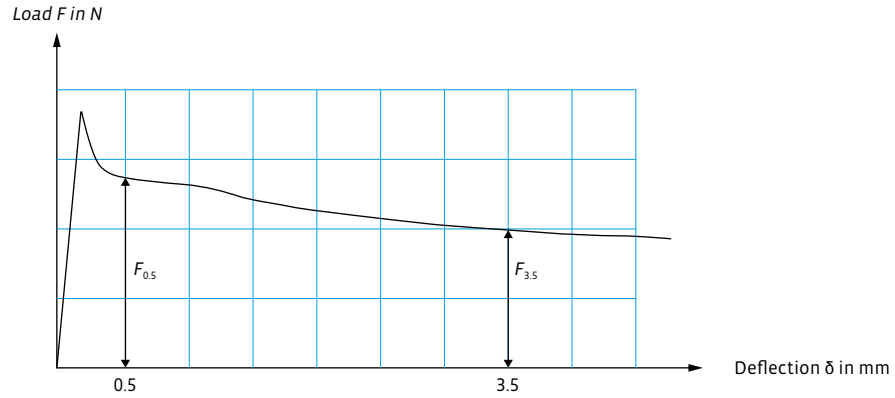


Figure 8: Load-deflection relationship for determining the post-cracking bending tensile strengths [2]

From a test series consisting of at least 6 beams, the average post-cracking bending tensile strengths of the test series for L1 and L2 are calculated as follows:

$$f_{cf1m,L1}^f = \frac{1}{n} \sum_{i=1}^n \frac{F_{0.5,i} \cdot l}{b_i \cdot h_i^2} \quad \text{in N/mm}^2 \quad (6)$$

$$f_{cf1m,L2}^f = \frac{1}{n} \sum_{i=1}^n \frac{F_{3.5,i} \cdot l}{b_i \cdot h_i^2} \quad \text{in N/mm}^2 \quad (7)$$

$l, b, h$  Span length, width and height of the specimen in mm;

Index  $i$  Beam number.

The characteristic values of the post-cracking bending tensile strength  $f_{cf1k,Li}^f$  for the classification of the steel fibre reinforced concrete into the performance classes L1 and L2 is determined according to this formula:

$$f_{cf1k,Li}^f = e^{(L f_{cf1m,Li}^f - k_s \cdot Ls)} \leq 0.51 \cdot f_{cf1m,Li}^f \quad \text{in N/mm}^2 \quad (8)$$

$L f_{cf1m,Li}^f$  Mean value of the logarithmized individual test results  $f_{cf1,Li,i}^f$  in N/mm<sup>2</sup>

$$L f_{cf1m,Li}^f = \frac{1}{n} \cdot \sum \ln(f_{cf1,Li,i}^f)$$

$Ls$  Standard deviation of the logarithmized single test results of the series;

$$LS = \sqrt{\frac{\sum(Lf_{clfm,Li}^f - \ln(f_{cfL,Li,i}^f))^2}{n-1}}$$

$k_s$  Fractile factor for unknown standard deviation for the 5 % quantile with 75 % confidence level according to Table 3.

Table 3: Fractile factor  $k_s$  [2]

number of specimens	Fractile factor $k_s$
6	2.336
9	2.141
12	2.048
15	1.991
20	1.932
25	1.895
100	1.760
$\infty$	1.645

NOTE: A modification of equation 8 at lower coefficients of variation is not allowed, since the  $\kappa_G^f$ -value (cf. Part 1, Section R.3.6.3 in [2]), were calibrated for the prefactor 0.51.

For the load-deflection curve, there must be a monotonic progression between  $\delta_{L1} = 0.5$  mm and  $\delta_{L2} = 3.5$  mm. If this is not the case, take the lowest value of the post-cracking bending tensile strength ( $F'_{3.5}$ ) between  $\delta_{L1} = 0.5$  mm and  $\delta_{L2} = 3.5$  mm for  $\delta_{L2} = 3.5$  mm and insert it in Equation 7. The procedure can be seen in Figure 9.

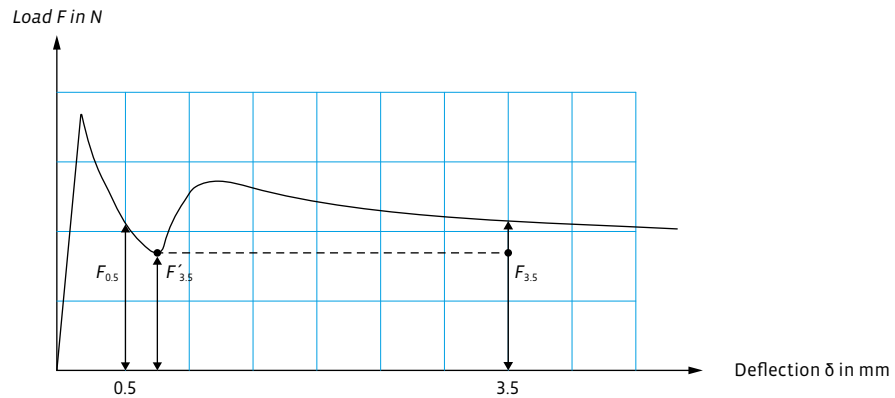


Figure 9: Evaluation of the load-deflection relationship for deviating curves [2]



The following table can be used to derive the performance class on the basis of the determined characteristic values of the post-cracking tensile strength  $f_{cf1k,L1}^f$  or  $f_{cf1k,L2}^f$ . In each case, select the performance class that is less than or equal to the calculated characteristic post-cracking bending tensile strength  $f_{cf1k,L1}^f$  or  $f_{cf1k,L2}^f$ .

Example:

For  $f_{cf1k,L1}^f = 1.21 \text{ N/mm}^2$ , the performance class L1 is 1.2.

For  $f_{cf1k,L2}^f = 0.89 \text{ N/mm}^2$ , the performance class L2 is 0.6.

As already explained, the characteristic values of the post-cracking bending tensile strengths  $f_{cf1k,Li}^f$  are obtained as 5 % fractile values of the average post-cracking bending tensile strengths. These fractile values are used to classify the steel fibre reinforced concrete into the performance classes according to Table 4. Usually, the value of performance class L1 is larger than the corresponding value of performance class L2. According to Table 4, the range of performance classes comprises characteristic post-cracking tensile strengths  $f_{cf1k,Li}^f$  between 0.4 and 3.0 N/mm<sup>2</sup>.

**Table 4:** Performance classes L1 and L2 for steel fibre reinforced concrete with corresponding basic values of the centric post-cracking tensile strengths [2].

Column	1	2	3	4	5
	Basic values of the centric post-cracking bending tensile strength $f_{cto}^f$ in N/mm <sup>2</sup>				
	Deformation 1		Deformation 2		
Row	L1	$f_{cto,L1}^f$	L2	$f_{cto,L2}^f$	$f_{cto,u}^f$
1	0	< 0.16	0	–	–
2	0.4 <sup>a</sup>	0.16	0.4 <sup>a</sup>	0.10	0.15
3	0.6	0.24	0.6	0.15	0.22
4	0.9	0.36	0.9	0.23	0.33
5	1.2	0.48	1.2	0.30	0.44
6	1.5	0.60	1.5	0.38	0.56
7	1.8	0.72	1.8	0.45	0.67
8	2.1	0.84	2.1	0.53	0.78
9	2.4	0.96	2.4	0.60	0.89
10	2.7 <sup>b</sup>	1.08	2.7 <sup>b</sup>	0.68	1.00
11	3.0 <sup>b</sup>	1.20	3.0 <sup>b</sup>	0.75	1.11

<sup>a</sup> Only for structural components with a large surface area ( $b > 5\%$ ).

<sup>b</sup> For steel fibre reinforced concrete of these performance classes proof of usability is required.

Example according to [2]:

“C30/37 – L1.2/0.9 – XC1 – WO”

Where

- C30/37 compressive strength class of the concrete according to DIN EN 206-1 in conjunction with DIN 1045-2
- Characteristic compressive strength on the cylinder ( $f_{ck,cyl}$ ) = 30 N/mm<sup>2</sup> or on the cube ( $f_{ck,cube}$ ) = 37 N/mm<sup>2</sup>
- Performance class L1: 1.2 (serviceability limit state)
- Characteristic post-cracking bending tensile strength  $f_{cf1k,L1}^f \geq 1.2$  N/mm<sup>2</sup>
- Performance class L2: 0.9 (ultimate limit state)
- Characteristic post-cracking bending tensile strength  $f_{cf1k,L2}^f \geq 0.9$  N/mm<sup>2</sup>
- All strength values are always characteristic values after statistical evaluation.
- XC1: Exposure class
- WO: Moisture class

NOTE: Performance class L1 is usually larger than or equal to performance class L2.

The guideline [2] allows linear interpolation for the determination of initial test results if the following conditions and the listed procedure are observed. On the one hand, an interpolation regarding the steel fibre content for the same strength class and, on the other hand, an interpolation regarding to the concrete strengths for the same fibre content is allowed.

Interpolation with respect to the steel fibre content at the same strength class and interpolation with respect to the concrete strengths at the same fibre content is made possible.

When **interpolating the steel fibre content at the same strength class**, the steel fibre reinforced concretes, which may only differ by a difference in fibre content of a maximum of 20 kg/m<sup>3</sup>, must have been tested in accordance with the procedure and framework conditions presented in the context of this white paper (cf. also Annex O of the DAfStb guideline [2]).

If this is the case, it is permissible to determine the average post-cracking bending tensile strength by linear interpolation for further concretes between the two tested fibre contents. Only variations in the concrete compositions at the plasticizer or superplasticizer content may be present. The guideline allows for the calculation of the characteristic values – calculation basis is equation 8 – to use interpolated standard deviations for simplicity. Interpolation considering the performance class L0 and/or a performance class larger than L2.4 is not allowed.

Furthermore, **interpolation of the concrete compressive strength class is possible with the same fibre content**. The prerequisite for this is that two concretes with the same concrete constituents have been tested in accordance with Annex O of the “Steel Fibre Reinforced Concrete “ guideline [2]. One concrete has a low compressive strength class (e.g., C20/25) and the other concrete a higher compressive strength (e.g. C35/45). For the intermediate concrete compressive strength classes, an interpolation of the mean post-cracking bending tensile strength proportional to the ratio of the mean tensile strengths  $f_{ctm}$  of the respective concretes according to DIN EN 1992-1-1 [8, 9] may be performed linearly.

Concretes with identical parent materials must meet the following requirements:

- Aggregates of the same geological origin;
- Same cement type and cement strength class;
- Additive of the same type;
- Admixtures of the same type.

The performance of steel fibres according to EN 14889-1 [5] in concrete is determined by the residual (post-cracking) flexural strength. The determination of the flexural strength of concrete with steel fibres is carried out on separately manufactured specimens.

Internationally, the 3-point bending test according to EN 14651 [1] is predominantly used. In Germany, the 4-point bending test according to the DAfStb guideline “Steel

Fibre Reinforced Concrete” [2] is (still) used, which is also partly used in other European countries.

**The reliable and economical use of steel fibre reinforced concrete is only possible if the specimens for the bending tests – regardless of whether for the 3- or 4-point bending test – are manufactured and tested according to the specifications.“**

The reliable and economical use of steel fibre reinforced concrete is only possible if the specimens for the bending tests – irrespective of whether for the 3- or 4-point bending test – are manufactured and tested in accordance with the

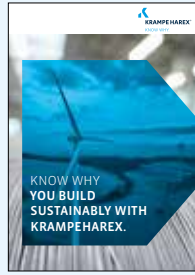
specifications. Furthermore, the correct evaluation and interpretation of the test results are of elementary and central importance. Reproducible and comparable results are essential for the correct evaluation and classification of the performance of steel fibre reinforced concrete. By following the explanations in this white paper, common errors in the production, testing and classification of steel fibre reinforced concrete can be avoided.

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