Round robin test to compare flexural strength test methods for steel fiber-reinforced sprayed concretes

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Abstract
According to the current European standard EN 14487-1 (residual) flexural strengths of steel fiber-reinforced sprayed concrete are determined by performing a four-point bending test on beams according to EN 14488-3. Controversial to this test method, a three-point bending test on notched square panels is recommended by EFNARC. According to EFNARC, one substantial advantage of this test method is the minor scattering of the test results. Against this background, a round robin test was performed at European level. The aim was to investigate the comparability and correlation on the one hand, on the other hand to assess the precision of both test methods. The results shall provide initial pointers for the classification of the residual strengths for steel fiber-reinforced sprayed concrete with two different test methods. The results showed that the scattering of the residual strengths is marginally smaller with the test method on panels in comparison to the test method on beams. As a result, a slightly higher precision was achieved. Therefore, the EFNARC test shall be included as an alternative test procedure in EN 14487-1 in future.

KEYWORDS
fiber-reinforced sprayed concrete, flexural strength, four-point bending test on beams, residual strength, three-point bending test on panels

1 | INTRODUCTION

The specification of the ductility of fiber-reinforced sprayed concretes is based on the classification of the residual strengths and/or energy absorption capacity according to EN 14487-1. In practice, residual strengths are usually determined for the case that the material properties of the concrete are required for a structural design model. Thereby, the classification of the residual strengths is specified by a strength level or rather a minimum strength in a certain deformation range. In EN 14487-1 the test method for the determination of the residual strengths is defined as a four-point bending test on beams according to EN 14488-3. To determine the structural properties of fiber-reinforced sprayed concretes with regard to the main field of application in tunneling as realistically as possible, a further test method was developed by the “National Railway Company (SNCF)” in France, which is included in the recommendations of
EFNARC (EFNARC: Experts for Specialized Construction and Concrete Systems) as well as in EN 14487-1 by EN 14488-5. This test method is used to determine the energy absorption capacity on square panels, which are supported on their four edges and loaded centrally with a point load. In this way, the typical loading scenario in tunneling in terms of biaxial bending can be simulated as realistically as possible. Analogous to the residual strengths the classification of the energy absorption capacity is also specified by defined minimum values at various deflections. However, in EN 14487-1 it is explicitly pointed out that a direct comparison of the different types for specification of the flexural strength behavior of fiber-reinforced sprayed concretes by the residual strength and energy absorption capacity is not feasible. Depending on the project-specific requirements on sprayed concretes it can be therefore necessary to perform both test methods. In this case, two different types of specimens have to be prepared and tested under different testing conditions, consequently.

In a 2011 published guideline by EFNARC a further test method for determining the flexural strengths of steel fiber-reinforced sprayed concrete is recommended as an alternative to the test procedure on beams according to EN 14488-3. Similar to the test method for concrete with metallic fibers according to EN 14651 (a three-point bending test on notched beams), this is a three-point bending test on notched panels. One advantage of this test method is certainly that the geometry and dimensions of the panels correspond to those of the test method for the determination of the energy absorption capacity according to EN 14488-5. Hence, only one type of specimen is necessary for the determination of the residual strengths and the energy absorption capacity.

While the test method according to EN 14651 is known to lead to a large scattering with regard to the residual strength (coefficients of variation are usually in the range of 20%–30%), initial comparative studies have shown that the test method according to EFNARC tends to lead to a significantly lower scattering (coefficients of variation between 6% and 22%). Although EFNARC declares that the scattering of test results is also lower compared with the test method on beams according to EN 14488-3, however, this has not yet been proven by appropriate comparative studies.

Therefore, it is necessary to verify if the scattering of the test results obtained by the test method according to EFNARC is actually lower than by the test method according to EN 14488-3, particular as in both guidelines it is noted, that there is no recognized data for the precision of the test methods. This should be investigated in the scope of a European round robin test within the revision of the European standard by the CEN TC104/WG10.

### 2. TEST METHODS

#### 2.1 Flexural strengths on beams (EN 14488-3)

For the determination of the flexural strengths (first peak, ultimate, and residual) according to EN 14488-3 beam specimens with the dimensions of 75 mm (height) × 125 mm (width) × 500 mm (minimum length) are prepared out of a sprayed panel. The beams are tested in a four-point bending test (Figure 1). The distance between the supporting rollers is 450 mm and between the loading rollers 150 mm. The applied load is measured as a function of deflection.

From the load–deflection curve the ultimate flexural strength $f_{ult}$ and the first peak strength $f_{fp}$ are determined (Figure 2a). In consistency with the residual strength classes defined in EN 14487-1, the residual strengths ($f_{R1}$, $f_{R2}$, and $f_{R4}$) are calculated from the minimum loads within the deflection intervals $D_1$ (0.5–1 mm), $D_2$ (0.5–2 mm), and $D_3$ (0.5–4 mm), as shown in Figure 2b.

#### 2.2 Flexural strengths on panels (EFNARC guideline)

Analogous to the test method for concrete with metallic fibers according to EN 14651 the flexural strengths are determined on notched panels with the dimensions of 600 mm (width) × 600 mm (length) × 100 mm (height) in a three-point bending test (Figure 3). The notch depth is 10 mm and correspondingly the effective cross section in the mid-span ($h_{sp}$) is 90 mm. The distance between the supporting rollers is 500 mm. On the construction site the panels should be sprayed in appropriate molds (sprayed concrete boxes). Usually, the applied load and the displacement at the crack mouth opening (Crack Mouth Opening Displacement [CMOD]) are measured.

![Figure 1](image-url) **Test setup according to EN 14488-3**

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Alternatively, the deflection can be measured at mid-span and converted by using the CMOD–deflection-relation.\(^5\) From the load–CMOD-curve the ultimate flexural strengths \(f_{ult}\) and the limit of proportionality \((LOP) f_{ct,L}\) are determined (Figure 4a). Analogous to EN 14651\(^6\) the residual strengths \(f_{R1}, f_{R2}, f_{R3}, \) and \(f_{R4}\) in this test method are defined in accordance with the Model Code 2010.\(^10\)

As shown in Figure 4b, they are determined from the loads \(F_{R1} (CMOD_1 = 0.5 \text{ mm}), F_{R2} (CMOD_2 = 1.5 \text{ mm}), F_{R3} (CMOD_3 = 2.5 \text{ mm}), \) and \(F_{R4} (CMOD_4 = 3.5 \text{ mm})\). The classification according to EN 14487-1\(^1\) is therefore not feasible on the basis of this test method, because the residual strength classes in EN 14487-1\(^1\) refer to the deflection intervals \(D_1, D_2, \) and \(D_3\) defined for the beams according to 14488-3\(^2\) (see Section 2.1).

## 3 | ROUND ROBIN TEST

### 3.1 | General

In order to assess the comparability between the two test methods and their precision (repeatability and reproducibility), a round robin test was performed at European level in five different laboratories (located in Germany, Belgium, France, and Italy). The round robin test was coordinated by the Institute for Building Materials of the Ruhr University Bochum in Germany.
3.2 Materials

The test specimens were produced by wet spraying using the base mix listed in Table 1. The strength class was C30/37. It is well-known that the fiber content has a significant influence on the scattering of the residual strengths (i.e., the lower the fiber content, the higher the scattering). Since the focus of the round robin test was on the comparison between the in Section 2 described test methods, the fiber content of the base mix was 50 kg/m³ and thus at the upper limit of usual contents for steel fiber-reinforced sprayed concrete in tunneling. The characteristic properties of the used steel fibers are shown in Table 2. Sand and gravel with a maximum grain size of 8 mm were used as aggregates. The dosage of the alkali-free accelerator injected at the nozzle was 5.5%.

3.3 Production and preparation of the test specimens

All test specimens were produced in wet-spraying process using a spraying robot at the Ruhr University Bochum. This should ensure the most realistic and practical boundary conditions, similar to those that prevail in situ in real tunnel construction projects. Due to the specific adjustment of the process-technological parameters on the spraying robot, a high reproducibility in the production of the specimens could be ensured. Figure 5 shows a schematic illustration and a photo of the spraying concrete test facility.

The base mix was delivered from a local ready-mix concrete plant to the laboratory of the Ruhr University Bochum. Immediately after delivery, the fresh concrete was assessed with regard to its workability and pumpability by means of testing the consistency (flow spread according to EN 12350-5) and the air content (EN 12350-7). Furthermore, cube specimens (150 x 150 x 150 mm³) were produced to prove conformity and to determine the actual fiber content of the base mix.

The distribution of the steel fibers already added to the ready-mixed concrete plant was also first checked visually. In addition to the consistency (flow spread according to EN 12350-5), the density (EN 12350-6) and the air content (EN 12350-7) of the base mix were determined. Furthermore, cube specimens (150 x 150 x 150 mm³) were produced to prove conformity and to determine the actual fiber content of the base mix.

The base mix was pumped to the spraying robot and sprayed through the nozzle (Ø = 42 mm) onto a pre-wetted vertically fixed pallet, whereby the accelerator was injected at the nozzle. The robot guided the nozzle according to a defined programmed motion sequence in horizontal and vertical direction including a rotating movement with a distance to the pallet of about 1.0 m.

For the production of the panels for the test method according to EFNARC,5 the required layer thickness of 10 cm was achieved by stripping the sprayed concrete surface with a steel profile immediately after spraying execution. In accordance with the specifications of EFNARC,5 this should prevent subsequent costly surface treatment (e.g., cutting, grinding) of the hardened sprayed concrete. For this reason, it was necessary to adjust the accelerator dosage in such a way that the solidification process of the sprayed concrete just progressed to such an extent that on the one hand it remained stable in form in several layers on the vertical pallet. On the other hand the stripping of the sprayed concrete surface should be still possible. In preliminary tests, an accelerator dosage of 5.5% was proven to be optimal for the used base mix (see Table 1). For the production of the beams, it was not necessary to strip the sprayed concrete surface since the beams were sawn out of the sprayed concrete pallets including their top sides according to the specifications of EN 14488-3.2 Figure 6 shows two different pallets with sprayed concrete for the production of the beams (Figure 6a) and panels (Figure 6b).

After the spraying process, the sprayed concrete was covered with moist jute and plastic foil for 24 h. Then the beams (125 mm x 75 mm x 600 mm) and panels (600 mm x 600 mm x 100 mm) were sawn out of the pallets. The panels were additionally notched with a diamond saw according to EFNARC.5 The required
dimensions (width $\leq 5 \text{ mm}$, depth $= 10 \text{ mm}$, Figure 3) were controlled with a depth caliper. It should be noted, when panels are produced on the construction site, they are usually sprayed into square molds, which is recommended by EFNARC. However, in this case the orientation of fibers in the edge regions of the panels would be influenced. As a result, the fibers in these regions tend to orientate in parallel to the side edges and thus, also in parallel to the bending tensile stresses during the three-point bending test, which could lead to a positive impact on the postcracking tensile capacity. Even though this effect can be assumed negligible due to the wide cross-section of the panels, the panels were sawn on all side edges. To determine the compressive strength of the hardened sprayed concrete, also drilling cores ($\varnothing = 100 \text{ mm}$, $L = 100 \text{ mm}$) were taken from the sprayed concrete pallets. The prepared specimens were cured for 7 days in a fog chamber (relative air humidity $\geq 95\%$; air temperature: $20^\circ\text{C} \pm 2^\circ\text{C}$) in accordance to EN 12390-2.14 Afterwards, the specimens were stored at an air temperature of $20^\circ\text{C} \pm 2^\circ\text{C}$ and a relative humidity of $65\% \pm 5\%$ until transport to the participating laboratories. In total, 18 beams and 24 panels were produced and prepared. Each of the five laboratories received three randomly selected beams and four panels. The remaining samples were retained as reserve samples.

3.4 | Testing the flexural strengths

In order to avoid potential effects of inherent stresses due to shrinkage, the test specimens were stored under water in the respective laboratories for 1 week before and until the beginning of the test (requirements according to EN 14488-3² or EFNARC⁵: at least 3 days). In each laboratory three beams were tested according to EN 14488-3² and four panels according to EFNARC⁵ (in total: 15 beams/20 panels). The age of the specimens at the time of testing was $60 \pm 2 \text{ days}$. The test age was chosen in order to require an advanced hydration process and therefore a degree of hydration as identical as possible for all test specimens. All laboratories were instructed to comply
with the test specifications\textsuperscript{2,5} as precisely as possible. Figure 7 shows an example of the test setup from various laboratories for the bending tests on beams according to EN 14488-3\textsuperscript{2} (Figure 7a) and on panels according to EFNARC\textsuperscript{5} (Figure 7b).

4 | RESULTS

4.1 | Fresh and hardened concrete properties

To ensure a sufficient pumpability, a very soft to flowable consistency of the ready-mix concrete was essential. This could be achieved by the addition of a superplasticizer (see Table 1). The flow spread of the ready-mix concrete was determined immediately before spraying and varied between 620 and 540 mm. The fresh concrete properties of the base mix are shown in Table 3.

The fiber content of the base mix was determined non-destructively by electromagnetic induction\textsuperscript{15} and ranged between 46 and 53 kg/m\textsuperscript{3}. The fiber content of the shotcrete was not determined. Even though, it is common knowledge that the actual fiber content of shotcrete is significantly lower after spraying process due to rebound, it could be expected that the loss of fibers was nearly the same for the panels as well as for the beams because all test specimens were produced under identical conditions with an automated sprayed concrete\textsuperscript{15} testing unit.

The conformity check according to EN 206\textsuperscript{16}/DIN 1045-1\textsuperscript{17}—based on compressive strength tests according to DIN EN 12390-3\textsuperscript{18} on cube specimens of the basic mix of each concrete batch (without accelerator) – exhibited a concrete strength class of C30/37 ($f_{cm,cube,28d} = 46$ N/mm\textsuperscript{2}). The compressive strength of the shotcrete, determined on drill cores taken from the shotcrete pallets, reached an average of 55 N/mm\textsuperscript{2} at the time of testing (60 ± 2 days).

4.2 | Flexural strengths

Figures 8 and 9 display the stress–deflection curves respectively the stress-CMOD curves of all specimens tested in the round robin test and in the respective laboratories (Lab A to E) (beams according to EN 14488-3\textsuperscript{2}: B1-15; panels according to EFNARC\textsuperscript{5}: P1-20).

The stress–deformation curves (Figures 8a and 9a) are typical for fiber-reinforced concrete under bending stress. At the beginning of loading the curves show a steep increase, which represents the initial stiffness. It can be seen that the initial stiffness of the beams and panels are almost identical in each case (Figures 8b and 9b). The average initial stiffness of the panels is approximately 253 MPa/(mm–δ) (equivalent to 320 MPa/[mm–CMOD]), which is six times higher than the average initial stiffness of the beams, which is 42 MPa/(mm–δ). This can be explained by the elastic section modulus (uncracked state), which is also higher by approximately this factor for the panels, compared with the beams ($W_{y,panels}/W_{y,beams} \approx 81 \times 10^4 \text{ mm}^3 / 11.7 \times 10^4 \text{ mm}^3 = 6.9$).

After the first crack and thus reaching the first stress maximum, an abrupt drop of the respective curve can be observed. With increasing deformation, the flexural tensile stresses are transferred—at least partially—by the crack-bridging steel fibers across the crack flanks. This ductile postcracking behavior is characterized by the more or less horizontal shape of the stress–deformation curves in the postcracking area. As was to be expected for steel fiber-reinforced (sprayed) concrete, a large scattering between the individual curves can be seen for both beams and panels in the postcracking area. The stress–CMOD curves of the panels clearly show a further stress increase, which leads to a further stress maximum in the range between 0.5 mm ≤ CMOD ≤ 2.0 mm. This is followed by a successive reduction of flexural tensile stresses as the deformation increases. The

FIGURE 7  Photo of the test setup for (a) beams according to EN 14488-3\textsuperscript{2} and (b) panels according to EFNARC\textsuperscript{5}
stress–deflection curves of the beams also partly show further stress increases in the postcracking area. Compared with the stress–CMOD curves of the panels, however, the stress–deflection curves of the beams are characterized by a very unsteady course in the postcracking area so that no exact range of the stress maximum can be localized. From a global point of view, a successive stress reduction can also be observed for the beams in the postcracking area. The much smoother shape of the curves of the panels in the postcracking area can be attributed, among other things, to the larger cross-sectional area of the panels and the resulting higher number of crack-bridging fibers.

From the stress–deformation curves of the beams and panels the corresponding flexural strengths were evaluated. The flexural strengths were determined according to EN 14488-3. The stress–deflection curves of the beams were determined using a crosshead displacement rate of 0.05 mm/s, whereas the stress–CMOD curves of the panels were determined using a crosshead displacement rate of 0.01 mm/s. The stress–CMOD curves of the panels were determined according to EFNARC5, which employs a crosshead displacement rate of 0.05 mm/s. The stress–deflection curves of the beams were determined for a range of deflections from 0 to 4 mm, whereas the stress–CMOD curves of the panels were determined for a range of crack mouth opening displacements (CMOD) from 0 to 0.3 mm and 0 to 0.1 mm.

### TABLE 3 Fresh concrete properties (base mix)

| Property          | Test method | Average values |
|-------------------|-------------|----------------|
| Flow spread       | EN 12350-510 | 580            |
| Density           | EN 12350-611 | 2.30           |
| Air content       | EN 12350-712 | 2.1            |

![Stress–deflection curves determined on beams according to EN 14488-3 in the range of (a) 0–4 mm and (b) 0–0.3 mm](image1.png)

**Figure 8** Stress–deflection curves determined on beams according to EN 14488-3 in the range of (a) 0–4 mm and (b) 0–0.3 mm

![Stress–CMOD curves determined on panels according to EFNARC5 in the range of (a) 0–5 mm and (b) 0–0.1 mm](image2.png)

**Figure 9** Stress–CMOD curves determined on panels according to EFNARC5 in the range of (a) 0–5 mm and (b) 0–0.1 mm
determined (see Section 2). To quantify the scattering, the lab-specific and overall average values $MV$, standard deviations $s$, and coefficients of variation $v$ were calculated for the respective flexural strengths. The results are shown in Figures 10 and 11.

Despite significant differences in specimen geometries and test conditions, the overall average of the ultimate flexural tensile strengths ($f_{ult,beam} = 4.68$ MPa; $f_{ult,panel} = 4.70$ MPa) are almost identical for both test methods (Figures 10a and 11a). The scattering within the individual laboratories is also very similar ($0.22 \text{ MPa} \leq s_{f_{ult,beam,lab,i}} \leq 0.44$ MPa, $0.22 \text{ MPa} \leq s_{f_{ult,panel,lab,i}} \leq 0.42$ MPa). Regarding the total scattering of ultimate flexural tensile strengths, it can be seen that this is marginally lower for the test procedure on beams ($s_{f_{ult,beam,total}} = 0.33$ MPa) than for the test procedure on panels ($s_{f_{ult,panel,total}} = 0.48$ MPa).

Both the absolute values and the scattering of the first peak strengths $f_{fp}$ and the limits of proportionality $f_{ct,L}$ differ only marginally from those of the ultimate flexural strength $f_{ult}$ (compare Figure 10a with Figure 10b and Figure 11a with Figure 11b). This is due to the subcritical

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**FIGURE 10** Flexural strengths—(a) $f_{ult}$, (b) $f_{fp}$, (c) $f_{R1}$, (d) $f_{R2}$, and (e) $f_{R4}$ determined on beams according to EN 14488-3²
Characteristic of steel fiber-reinforced concrete with subcritical fiber contents is a decline in stress after reaching the first peak stress due to a macrocrack formation, that is, the fiber content is too low to sufficiently bear the tensile stresses that occur and to develop multiple cracking. In this case the post-cracking stresses usually do not exceed the first peak crack strength or the limit of proportionality. As a result, $f_{ult}$ is equal to $f_{fp}$ or $f_{ftrL}$, respectively. However, in some exceptional cases (beams B2 and B14; panels P3 and P19), slightly larger values were determined for $f_{ult}$ ($\Delta_{\text{max, beam}} = f_{ult} - f_{fp} = 0.40 \text{ MPa}$, $\Delta_{\text{max, panel}} = f_{ult} - f_{ctL} = 0.20 \text{ MPa}$). In these cases, it can be assumed that a comparatively beneficial fiber distribution and/or fiber orientation was present in the crack area of the test specimens.

The average residual strengths $f_{Ri}$ of the beams (Figure 10c–e) are below the ultimate flexural strengths and the first peak strengths and decrease in sequence (i.e., with an increasing deflection interval) ($f_{R1} = 3.45 \text{ MPa} > f_{R2} = 3.26 \text{ MPa} > f_{R4} = 2.75 \text{ MPa}$). As expected from Figure 8a, the total scattering of the

![Figure 11](image-url)
residual strengths is significantly larger than the total scattering of the ultimate flexural tensile strengths and the first peak strengths (0.52 MPa ≤ \(s[f_{Ri,\text{total}}]\) ≤ 0.62 MPa). The scattering of the residual strengths between the laboratories is also almost significantly larger than the scattering of the ultimate flexural strengths and first peak strengths.

For the panels (Figure 11c–f), similar average values were obtained for the residual strengths \(f_{R1}\) and \(f_{R2}\). Here \(f_{R2}\) (4.07 MPa) is even slightly higher than \(f_{R1}\) (3.93 MPa). From \(f_{R2}\) onwards, the residual strengths also decrease in sequence with increasing CMOD (\(f_{R2} = 4.07\) MPa > \(f_{R3} = 3.73\) MPa > \(f_{R4} = 3.26\) MPa). In contrast to the test results of the beams, the total scattering of the residual strengths determined on panels is in a similar range as the total scattering of the ultimate flexural strengths and the limits of proportionality (0.43 MPa ≤ \(s[f_{Ri,\text{total}}]\) ≤ 0.55 MPa). Within the individual laboratories, however, significantly larger scattering is recognizable in some cases.

A comparison of the results between beams and panels demonstrates that the scattering of the residual strengths for the test method according to EFNARC5 is on average marginally lower than for the test method according to EN 14488-3\(^2\) (0.43 MPa ≤ \(s[f_{Ri,\text{panel total}}]\) ≤ 0.55 MPa, 0.52 MPa ≤ \(s[f_{Ri,\text{beam total}}]\) ≤ 0.62 MPa). In contrast, the coefficients of variation \(v[f_{Ri,\text{total}}]\) relating to the mean values of the residual strengths are significantly lower for the test method according to EFNARC5 than for the test method according to EN 14488-3\(^2\) (12.5% ≤ \(v[f_{Ri,\text{panel total}}]\) ≤ 13.4%, 16.0% ≤ \(v[f_{Ri,\text{beam total}}]\) ≤ 22.2%) due to the comparatively larger mean values. However, as mentioned in the introduction, a direct comparison of the residual strengths between the investigated test methods is not possible due to their different definitions.

The marginally lower values and the larger scattering of the residual strengths within the test method on beams according to EN 14488-3\(^2\) are also caused by the fact that the residual strengths are determined by the definition from the minimum of the flexural tensile stresses in the respective deflection interval, whereas the residual strengths of the panels according to EFNARC5 are determined at exactly defined CMOD values (see Section 2).

### 4.3 Precision of the test methods

The precision of both test methods was determined according to ISO 5725-2.\(^{19}\) Thereby, the precision is estimated by means of the repeatability standard deviation \(s_r\) and the reproducibility standard deviation \(s_R\). Those are calculated from the corresponding variances. The reproducibility variance \(s_R^2\) is composed of the repeatability variance \(s_r^2\) and the variance between the different laboratories \(s_L^2\) (Equation 1).

\[
s_R^2 = s_L^2 + s_r^2
\]

where, \(s_R^2\) is the estimate of the between-laboratory variance, \(s_r^2\) the arithmetic mean of \(s_R^2\) (the estimate of the within-laboratory variance) and the estimate of the repeatability variance, this arithmetic mean is taken over for all those laboratories taking part in the accuracy experiment which remain after outliers have been excluded; and \(s_R^2\) the estimate of the reproducibility variance (Equation 1).

Before determining the variances according to ISO 5725-2,\(^{19}\) it is statistically important to identify outliers and exclude them from the calculation. The flexural strengths of the beams and panels were verified regarding potential outliers applying two different test methods proposed in ISO 5725-2\(^{19}\) (Cochran test and Grubbs test). However, no outliers were detected neither for the beams nor for the panels. Also the residual strengths for the beam “B7” are not considered as outliers, although the load–deflection curve in the postcracking area seems to be significantly different from those of the other test specimens (see Figure 8a).

Tables 4 and 5 show the determined values of precision for all flexural strengths of both test methods. In addition to the variances \(s_r^2\) and standard deviations \(s_r\), the corresponding coefficients of variation \(v_r\), related to the total mean value of the respective flexural strength, are listed.

As can be seen in the Tables 4 and 5, the calculation according to ISO 5725-2\(^{19}\) results in negative values for several between-laboratory variances \(s_L^2\). This inconsistent result is due to the statistical model “ANOVO” used in ISO 5725-2.\(^{19}\) It indicates that the scattering between the laboratories is not statistically significant in these cases. Since a variance by definition cannot have a negative value, \(s_L^2\) is set to zero in those cases.\(^{20}\)

Consistent with the results presented in Section 4.2, the reproducibility standard deviations \(s_R\) of the ultimate flexural strengths \(f_{ult}\) and first peak strengths \(f_{fp}\) or limits of proportionality \(f_{ult,L}\), respectively, are slightly lower for the test method on beams compared with the test method on panels (\(s_R[f_{ult,beam}] = 0.34\) MPa < \(s_R[f_{ult,panel}] = 0.50\) MPa, \(s_R[f_{fp}] = 0.35\) MPa < \(s_R[f_{ult,L}] = 0.51\) MPa). However, the precision values in Tables 4 and 5 show that the reproducibility standard deviations (average scattering within the laboratories) of these flexural strengths are approximately equal (\(s_R[f_{ult,beam}] = 0.31\) MPa ≈ \(s_R[f_{ult,panel}] = 0.34\) MPa, \(s_R[f_{fp}] = 0.33\) MPa ≈ \(s_R[f_{ult,L}] = 0.32\) MPa). The larger values for the reproducibility standard deviation \(s_R\) result from
TABLE 4  Precision values for the test method on beams according to EN 14488-3

| Precision parameter | \( f_{ul} \) | \( f_{fp} \) | \( f_{R1} \) | \( f_{R2} \) | \( f_{R4} \) |
|---------------------|---------|---------|---------|---------|---------|
| \( s_L^2 \) [MPa²]  | 0.019   | 0.014   | 0.035   | \(-0.011\) | 0.062   |
| \( s_r^2 \) [MPa²]  | 0.095   | 0.106   | 0.349   | 0.283   | 0.321   |
| \( s_R^2 \) [MPa²]  | 0.115   | 0.120   | 0.384   | 0.283   | 0.383   |
| \( s_L \) [MPa]     | 0.14    | 0.12    | 0.19    | 0       | 0.25    |
| \( s_r \) [MPa]     | 0.31    | 0.33    | 0.59    | 0.53    | 0.57    |
| \( s_R \) [MPa]     | 0.34    | 0.35    | 0.62    | 0.53    | 0.62    |
| \( v_L \) [%]       | 3.0     | 2.5     | 5.5     | 0       | 9.1     |
| \( v_r \) [%]       | 6.6     | 7.0     | 17.1    | 16.3    | 20.6    |
| \( v_R \) [%]       | 7.2     | 7.4     | 17.9    | 16.3    | 22.5    |

TABLE 5  Precision values for the test method on panels according to EFNARC

| Precision parameter | \( f_{ul} \) | \( f_{fp} \) | \( f_{R1} \) | \( f_{R2} \) | \( f_{R3} \) | \( f_{R4} \) |
|---------------------|---------|---------|---------|---------|---------|---------|
| \( s_L^2 \) [MPa²]  | 0.136   | 0.155   | \(-0.030\) | 0       | 0       | 0       |
| \( s_r^2 \) [MPa²]  | 0.113   | 0.105   | 0.266   | 0.346   | 0.297   | 0.222   |
| \( s_R^2 \) [MPa²]  | 0.250   | 0.260   | 0.266   | 0.346   | 0.297   | 0.222   |
| \( s_L \) [MPa]     | 0.37    | 0.39    | 0       | 0       | 0       | 0       |
| \( s_r \) [MPa]     | 0.34    | 0.32    | 0.52    | 0.59    | 0.55    | 0.47    |
| \( s_R \) [MPa]     | 0.50    | 0.51    | 0.52    | 0.59    | 0.55    | 0.47    |
| \( v_L \) [%]       | 7.9     | 8.4     | 0       | 0       | 0       | 0       |
| \( v_r \) [%]       | 7.2     | 6.9     | 11.0    | 12.6    | 11.7    | 10.1    |
| \( v_R \) [%]       | 10.6    | 10.9    | 13.1    | 14.5    | 14.6    | 14.4    |

The comparatively larger scattering between the laboratories (\( s_L[f_{ul,beam}] = 0.14 \) MPa < \( s_L[f_{ul,panel}] = 0.37 \) MPa; \( s_L[f_{fp}] = 0.12 \) MPa < \( s_L[f_{cl,l}] = 0.39 \) MPa).

The reproducibility standard deviations \( s_R \) of the residual strengths for the test method on panels tend to be marginally lower than for the test method on beams according to EN 14488-3\(^2\) (0.53 MPa ≤ \( f_{R1,beam} \) ≤ 0.62 MPa; 0.47 MPa ≤ \( f_{R1,panel} \) ≤ 0.59 MPa). However, due to the comparatively larger mean values of the residual strengths of the panels, the coefficients of variation \( v_R \) are significantly smaller than in the test method on beams (13.1% ≤ \( v_{R,panel} \) ≤ 14.6%, 16.3% ≤ \( v_{R,beam} \) ≤ 22.5%).

It should be emphasized that the number of test specimens within the scope of the round robin test was too low to be able to determine the precision of the test methods with a sufficiently high accuracy. In addition to a higher number of test specimens, further investigations are also necessary, for example with regard to other concrete mixtures, fiber contents, fiber types, and so on, in order to make reliable and universal statements on the precision of the test methods. It should be clear that lower fiber contents would lead to a significantly larger scattering and thus, to lower precision values for both test methods. Nevertheless, based on the presented precision values, a tendency toward a marginally higher precision for the test method on panels according to EFNARC\(^5\) could be detected with regard to the essential material property of steel fiber shotcrete—the residual bearing capacity. The results obtained here provide a basis for a more reliable determination of the precision.

## 5  SUMMARY AND CONCLUSION

According to the current European standard for sprayed concrete EN 14487-1,\(^1\) the flexural strengths (initial crack, flexural tensile strength and residual strength) of fiber-reinforced sprayed concretes must be determined through a four-point bending test on beams according to EN 14488-3\(^2\). An EFNARC guideline\(^5\) recommends an alternative test method in which the flexural strengths are determined in a three-point bending test on notched panels. An essential advantage of this test method is that the geometry and dimensions of the panels correspond to...
those of the test method for determining the energy absorption according to EN 14488-5, so that only one type of specimen is required for both tests. Furthermore, EFNARC mentions a lower scattering of results as an advantage of this test method.

Within the framework of CEN TC104/WG10, a round robin test was carried out at European level to compare both test methods and to assess their precision. For this purpose, steel fiber-reinforced sprayed concrete specimens (beams and panels) were produced using a spraying robot at the Ruhr University Bochum. The specimens were tested in five European laboratories.

With regard to the ultimate flexural tensile strengths as well as the first peak strengths and the limits of proportionality, there were no significant differences between both test methods, neither for the absolute values nor for the scattering. However, a marginally lower scattering could be detected for the test procedure on beams. A direct comparison between both methods regarding the residual strengths and their scattering is not possible due to the different definitions of the test methods. Based on the results of the round robin test, however, the tendency toward lower scattering and thus higher precision for the test method on panels according to EFNARC could be observed.

In future, the test method on panels according to EFNARC will be included in EN 14487-1 as an alternative test method. However, this requires further parameter studies on the one hand, and an adjustment of EN 14487-1 with regard to the classification of the residual strengths on the other.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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