UNI-AXIAL TENSILE TESTS FOR UHPFRC

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Abstract

The article summarizes the state of the art of uni-axial tensile tests of normal strength, fiber-reinforced and ultra-high performance concrete. The localization phenomenon observed in tensile testing is presented and special interest is paid to multiple-cracking in the case of strain-hardening materials. Problems of specimen anchorage are presented and explained with a micromechanics approach. A four-stage fracture model is used for fiber-reinforced concrete to highlight its particularities regarding the uni-axial tensile testing. Previous tests and available guidelines are critically reviewed and the main disadvantages highlighted. At the end, a robust uni-axial testing procedure is suggested for both strain-softening and strain-hardening materials. The suggested procedure should provide accurate and reliable data with advantages of simple and fast testing. With the new procedure, main disadvantages of the previous procedures are eliminated.

Résumé

L'article résume l'état de l'art des essais de traction uni-axiaux sur béton normal, béton fibré et à ultra-haute performances. Le phénomène de localisation observé dans les essais de traction est présenté et un intérêt particulier est accordé à la multi-fissuration dans le cas d'un matériau avec écrouissage. Les problèmes d'ancrage de l'échantillon sont présentés et expliqués avec une approche micro-mécanique. Le modèle de fracture en 4 phases est appliqué au béton fibré pour mettre en évidence ses particularités concernant les essais de traction uni-axiale. Les tests préexistants et les directives disponibles sont passés en revue et les inconvénients mis en évidence. À la fin, une procédure robuste de test uni-axial est proposée, aussi bien pour les matériaux adoucissants qu'écrouissants, qui devrait fournir des données précises et fiables avec les avantages des tests simples et rapides. Avec cette nouvelle procédure, les principaux inconvénients des procédures préalables sont éliminés.

1. INTRODUCTION

Experimental tests are crucial for determining material properties. Compression and uni-axial tension behavior are the most important characteristics of UHPFRC. Testing in compression is straightforward. By contrast, determination of uni-axial tensile properties is a difficult task. The most straightforward method is a uni-axial tensile test because it measures directly the desired properties. Unfortunately, the amount of guidelines that can be followed for UHPFRC is limited. This is why the methods, which were so far used for UHPFRC, were difficult to perform and had a low reliability of the results. The lower reliability was mainly caused by difficulties with evenly distributed stresses over the cross-section and/or uniformly opened cracks. Consequently, indirect test methods are often suggested to overcome disadvantages of the uni-axial tests such as 3-point or 4-point bending tests as proposed in the new French standard [1] or other methods such as a splitting test, a wedge-splitting test, a combination of two last tests: a double-edge wedge-splitting test, or a multi-directional double punch test.

SIA 2052 [2] is the only official standard that describes uni-axial testing of UHPFRC. Unfortunately, the defined test fails in providing the correct elastic properties. The original AFGC recommendations [3] suggest possible methods but no details are provided. Moreover, the recent French norm NF P 18-470 [1] derived from AFGC 2013 [3] does not anymore define any direct tensile tests. Which is why, this paper suggests a robust procedure of uni-axial tensile testing as it represents the most straightforward method. The procedure can be used for the complete description of material from the time of loading up to the complete failure.

2. KEY CHARATERISTICS OF THE UNI-AXIAL TENSILE TESTING

In general, the main problems with performing uni-axial tensile tests are related to two origins:

- Localization and multiple-cracking of the tested specimen;
- Anchorage of the tested specimen to a testing machine.

2.1 Localization and multiple-cracking of the tested specimen

When concrete localizes, a strain description of the response loses its informative capability (uniqueness) due to dependency on the measured length. Crack-opening-displacement (COD) is used instead of the strain to describe the concrete beyond its localization. However, the position of the crack is random and therefore notched specimens were often used to enforce the crack appearance within the measured area.

Another possibility for the determination of COD is eliminating the measured-length dependence by a post-treatment of the measured displacement. COD of the randomly localized crack can be deduced from the total displacement (δ), the measured length (l), the elastic modulus (E), the applied stress (σ), and the characteristic length in tension ($l_{ch,t}$) as:

$$\begin{aligned}
&\delta_i = COD_i + \delta_{unloading,i} = COD_i + \left(l - l_{ch,t}\right)\frac{\sigma_i}{E} \\
&COD_i >> \left(l - l_{ch,t}\right)\frac{\sigma_i}{E} \quad and \quad l >> l_{ch,t} \quad \Rightarrow \quad COD_i \approx \delta_i - l\frac{\sigma_i}{E}
\end{aligned} \tag{1}$$

where the subscript (Xi) stands for each loading step.

The notched approach does not require the post-treatment of the results. The risk of failure in the anchorage or outside of the measured zone is eliminated by its reduced cross-section. Yet, it enforces the crack localization into a predefined position, therefore it does not include randomness of the material, and consequently it overestimates its performance. The notch itself also creates stress concentrations in the tested specimen and therefore it is not suitable for evaluation of the cracking strength (σ_{cc}). RILEM TC 162-TDF [4] prescribes the use of a notched cylindrical specimen and suggests, according to the previous statement, that the cracking strength (σ_{cc}) should be determined independently.

UHPFRC may exhibit also strain-hardening behavior which makes a pure COD description incomplete. The notched setup and the COD description can still be used, but a crack spacing (s_{cr}) must be added to well represent its full structural behavior. Nonetheless, using the COD description for strain-hardening materials is somehow cumbersome as many cracks occur and their spacing is not clear. Consequently, the strain description is more appropriate before localization. A combination of the COD and strain can be used as shown in Figure 1b.

Figure 1 shows the alternative procedure for the post-treatment of the measured values from Wille et al. [5]: including a parametric study of the unknown parameters. If a cross-section (A) is constant over the measured length (l), COD can be determined from the total displacement (δ), the measured values at the maximum resistance (δ_{Fmax}, F_{max}), the residual strain and displacement (ε_{res}, δ_{res,F_max}) when unloaded from the peak, the residual stiffness (E_{pc}), and the characteristic length in tension ($l_{ch,t}$) as:

$$\delta_i = COD_i + \delta_{unloading,i} = COD_i + \left(l - l_{ch,t}\right)\left(\frac{\sigma_i}{E_{pc}} + \varepsilon_{res}\right) \qquad (2)$$

$$l >> l_{ch,t} \quad and \quad \frac{\sigma_i}{E_{pc}} + \varepsilon_{res} \approx \frac{\sigma_i}{E_{\min}} \quad \Rightarrow \quad COD_i \approx \delta_i - l\frac{\sigma_i}{E_{\min}} \qquad (3)$$

$$where: \quad E_{\min} = \frac{\sigma_{F\max}}{\delta_{F\max}/l} \quad E_{pc} = \frac{\sigma_{\max}}{\left(\delta_{F\max} - \delta_{res,F\max}\right)/l} \quad \sigma_{F\max} = \frac{F_{\max}}{A}$$

COD at the onset of the localization (COD_{pc}) should be determined and added to the stress-COD description (Figure 1 b & d) if the full description is needed. Fantilli et al. [6] proposed a model to predict the average crack spacing (scr) which then can be used for the determination of COD_{pc}:

$$COD_{pc} = \frac{\delta_{pc}}{l/s_{cr}} \qquad (4)$$

The example on Figure 1 was based on the values taken from Wille et al. [5]: 99% of the post-cracking strength (σ_{pc}) at the beginning of the softening phase (F_{max}), the initial stiffness (E_c) is 61GPa, the residual stiffness (E_{pc}) is 6.3GPa, the fiber length (l_f) is 13mm, and the measured crack spacing (s_{cr}) is 4.7mm.

Figure 1d shows small differences between the "Exact" and "Simple" equations (2 & 3). The figure also shows a parametric study of two normally unknown or uncertain parameters for the exact equation (2): the characteristic length in tension and the residual stiffness. Upper and lower bounds were considered for the two parameters to study the sensitivity of both, [0,

$l_f/2$] and [E_{min}, E_c], respectively. The results show a low sensitivity in both cases. The low sensitivity of the exact form (Eq.2) indicates that the simple form (Eq.3) should be sufficiently robust.

Figure 1b shows the results from the simplified formula (Eq.3) combined with the strain-hardening relationship up to the peak. One of the main benefits of the combined relationship, in comparison to the pure stress-COD relationship, is the lower sensitivity to uncertainty of the measurement. Any possible error of LVDT measurements over the whole length is reduced by a number of cracks whereas the error from the single crack measurement is multiplied in the other case: Another advantage of the combined relationship is related to FEM simulations where only a part of the material response must be adjusted according to the mesh size.

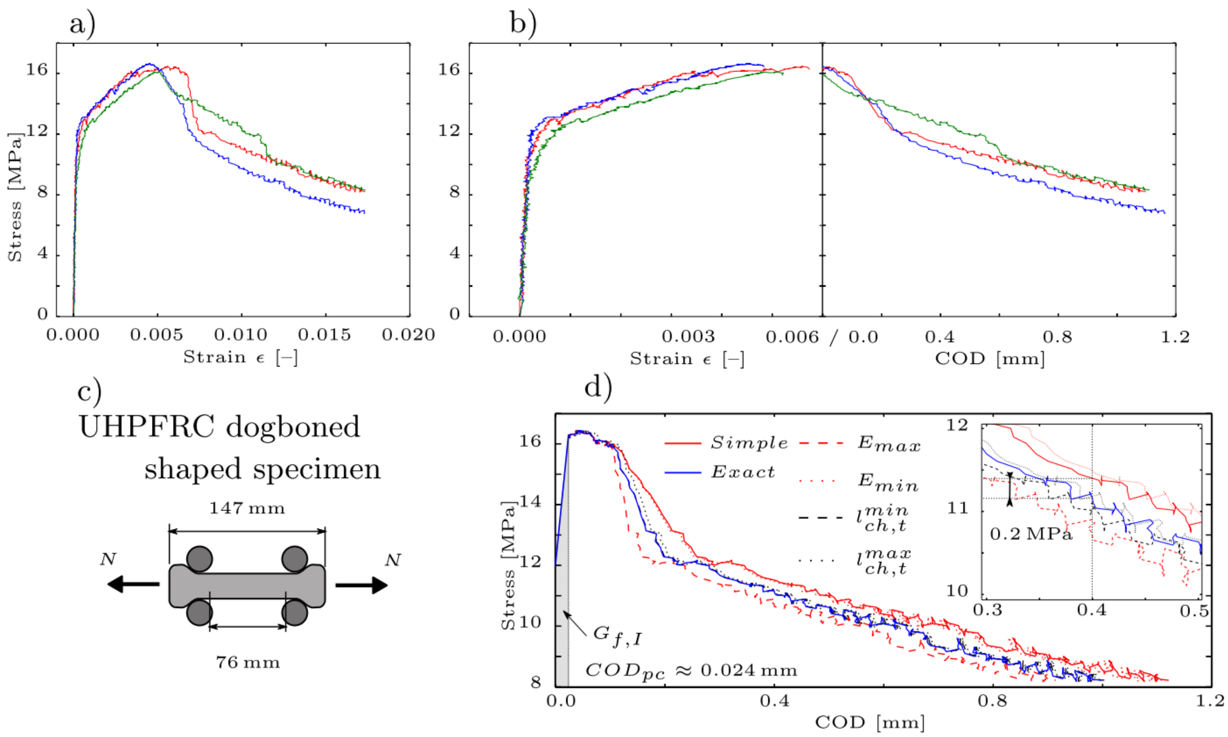

Figure 1: Post-treatment of the experimental results: (a) measured response in tension [5], (b) combined strain and COD description of material response intension, (c) experimental setup [5], and (d) COD description of the material response in tension

2.2 Anchorage of the tested specimen to a test machine

The anchorage of the tested specimens is a crucial factor for the proper performance of the uni-axial tensile tests. Imperfect connections between the specimen and the machine can cause a premature failure or create unintentional stresses (e.g. bending due to misalignment). Dogbone shaped specimens are often used to eliminate the premature failure. The main feature of the dogbone shaped specimens is a bigger cross-section at the support which: reduces the risk of failure in the glued area, reduces the risk of failure outside of the measured length, creates mechanical support to eliminate gluing for acceleration of the experimental procedure, allows simple casting, but makes extraction of the specimen from casted elements barely possible.

The anchorage itself significantly influences the measured values as it creates boundary conditions for the tested specimen. The boundary conditions can be divided into two groups based on the degree of freedom: tests that allow rotation of the ends and tests that restrain the ends. Figure 2 illustrates effects of the boundary conditions on the stress-displacement relationship and the fracture mechanism under uni-axial tension for NSC. Most of the research has been done on fiberless concrete, therefore the main features are here described on the fiberless concrete as well. The effects of fibers are discussed later in this article.

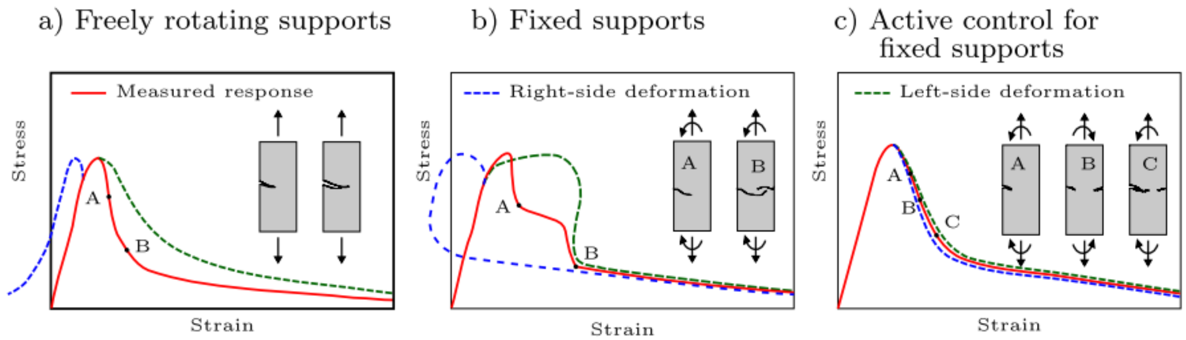

Figure 2: Effect of the boundary conditions on the stress-displacement relationship and the fracture mechanism under uni-axial tension for NSC: (a) Freely rotating supports; (b) Fixed supports; (c) Active control for the fixed supports (adapted from [7])

2.2.1 Freely rotating supports, Figure 2a

The freely rotating supports assure that no secondary loading from the gripping device is applied to the specimens during loading. Nevertheless, a crack always initiates at one side due to the heterogeneity of concrete and then the crack propagates to the other side. In this case, a non-uniform crack opening occurs and pure averaging of the measured values underestimates the real response. Indeed, Hordijk [8] with a simple model and Zhou [9] with a FEM model studied the effect of the boundary conditions. The studies showed "smooth" responses as in Figure a. The smoothness of the curve is caused by the freely rotating supports which eliminate "bump" effects. Nevertheless, the response is lower than in the case of the fixed supports. The apparent stress (F/A) is lower than the real stress due to the bending. Figure 2a (upper) illustrates that even a part of the specimen can be in compression (δ_2).

2.2.2 Fixed supports, Figure 2b

The fixed support tests were designed to ensure a uniform crack opening, thereby measuring more realistic average responses. A crack is still initiated at one side due to the heterogeneity of concrete (Figure 2b -Stage A) but the fixed supports create a moment in the opposite direction. The bending moment stops the crack propagation at one side and initiates another crack on the other side (Figure 2b - Stage B). Figure 2b (upper) shows that the curve is not smooth and the "bumps" are observed (between stage A and B). The "bumps" are caused by an insufficient stiffness of the experimental setup which creates the snap-back. The "bumps" are eliminated when the stiffness of the experimental setup is higher than a threshold. The stability criterion can be found in Zhou [9]. The condition is based on an assumption that the stabilizing moment should be greater than the moment due to eccentricity. Consequently, the specimen geometry must follow certain limits; otherwise "bump" effects occur. Hordijk [8] proved that the "bump" effect can be eliminated completely if the length of the specimen is sufficiently small.

Other disadvantages of the fixed supports are secondary bending stresses from a gripping device which can cause a local increase of stress. Consequently, the cracking strength (σ_{cc}) is underestimated. Indeed, Graybeal and Baby [10] observed an average difference of ~40% (10.8MPa/7.7MPa) between the cracking strength and the apparent cracking strength.

2.2.3 Active control for the fixed supports, Figure 2c

The active control tries to keep the uniform crack opening around the perimeter of the specimen by actively changing applied moments in two perpendicular directions.

2.2.4 Anchorage in the case of UHPFRC

The first question to answer before elaborating on the anchorage of UHPFRC specimens is: what are the real material properties? Some authors suggested that the softening part was not a pure material property as it could be easily influenced by the boundary conditions. Moreover, the impact of the softening part was low. In the case of UHPFRC, the situation is a little different because the post-peak part significantly contributes to the structural response.

From Figure 2, it can be observed that the main differences between supports occur in the immediate post-peak region where a macrocrack is formed (approximately until the point B). On the contrary, the subsequent responses have similar characteristics. In the case of NSC, the immediate post-peak region is important as it represents 60% of the total fracture energy. However, in the case of UHPFRC (or FRC), the immediate post-peak region represents only a small part of the total fracture energy due to the domination of the subsequent response. Moreover, it is not clear whether any inconsistency even occurs as the descending part after the peak does not have such a steep slope as does NSC. Indeed, tensile test experiments on FRC and UHPFRC showed that the descending part is much less steep [5, 10].

3. NORMS AND RECOMMENDATIONS OVERVIEW FOR UHPFRC

Standard tensile test methods for NSC can be perhaps used for determining the first cracking resistance (σ_{cc}) but cannot be used for the post-cracking phase. Methods developed for FRC [4] cover only strain-softening behavior, thus they cannot be used for all groups of UHPFRC. Consequently, a procedure(s) considering particularities of UHPFRC should be used to efficiently identify the desired tensile properties. The authors identified three relevant documents for UHPFRC:

- ***AFGC 2013 [3]*** are the French recommendations for UHPFRC used until 2016 which recommend the determination of the tensile constitutive law by bending or uni-axial tensile tests. The procedure is divided twice into two groups. The first group is for strain-softening materials and the second group is for strain-hardening materials including thin plates. In both groups, two types of tests are prescribed. The first test for elastic properties and the second test for the post-peak behavior. The elastic properties should be determined by un-notched prisms or cast diabolos (dogbone-like shape) for both groups. The post-peak behavior should be also determined with prisms or cast diabolos but with a notch in the case of the first group and without the notch otherwise. Nevertheless, no definition of the specimen geometry or the testing machine is provided and therefore arbitrary applications can give different results. Unfortunately, the recent French norm derived NF P 18-470 [1] derived from AFGC 2013 [3] does not define any direct tensile tests. Only indirect bending tests with inverse-analyses are supposed to be used for the determination of the tensile properties. Consequently, the new norm restricts AFGC [3] where the tensile testing is possible, although it is vaguely described.

- ***SIA 2052:2015 [2]*** is the recent Swiss standard for UHPFRC which defines a tensile test in Appendix D. The standard test specimen has a dogbone shape with dimensions at the measured zone of 30 × 50 × 200 mm^3 and a cross-section at the supports of 30 × 100 mm^2 .The specimen should be equipped with four displacement sensors one at each side. The support conditions are defined as fixed without the possibility of rotation of the specimen ends. The experimental results are intended to be used for determination of the elastic and non-linear properties.
- ***RILEM TC 162-TDF [4]*** describes a uni-axial tension test for steel fiber-reinforced concrete. The test is designed for strain-softening materials and should not be used for the determination of the cracking strength (σ_{cc}). The standard test specimen is cylindrical with a nominal diameter of 150mm and notched in the middle around the circumference. The notch has a depth of 15mm ± 1mm and a width of 2–5mm. The height of the specimen is 150mm. The restrained (fixed) supports are required on both sides. The maximum difference between at least 3 individual displacement transducers should be less than 10% of the mean displacement.

4. ROBUST UNI-AXIAL TENSILE TEST METHOD FOR UHPFRC

The overview of recommendations and standards together with the above described experimental difficulties indicate that there is no uni-axial tensile test method that would allow the complete description of the material. The only official norm that describes such a test is SIA 2052 [2]. Unfortunately, the defined test is similar to the tests performed by Graybeal and Baby [10] and Tailhan et al. [11] which fail in providing the correct elastic properties. The results [10, 11] clearly show the unintended bending during the elastic loading for the fixed supports. Such unintended bending strongly underestimates the elastic resistance when classical formulas, as those in SIA 2052:2015 [2], are used. Moreover, it is not clear whether such test set-ups [2, 10, 11] can be still considered as fixed supports beyond the onset of the localization as the multiple cracking occurred. Indeed, Graybeal and Baby [10] observed that even for the fixed supports the secondary bending was reduced due to the multiple cracking effect after a short period of early-cracking.

RILEM TC 162-TDF [4] can be efficiently used to determine the post-peak response but fails (as highlighted in the recommendation) to provide the correct elastic properties and for strain-hardening materials. The original AFGC recommendations [3] suggest a possible approach but no details are provided and the new French standard [1] omits it completely.

To the authors' best knowledge, a combination of two methods, the freely rotating and fixed supports seems to be an ideal solution for the complete description of material from the onset of loading up to the complete failure:

- An un-notched specimen with a constant cross-section at the central part loaded by the freely rotating supports to capture multiple cracking and the realistic cracking strength (σ_{cc}) including effects of the material heterogeneity;
- A notched specimen loaded by the fixed supports to capture the post-peak response.

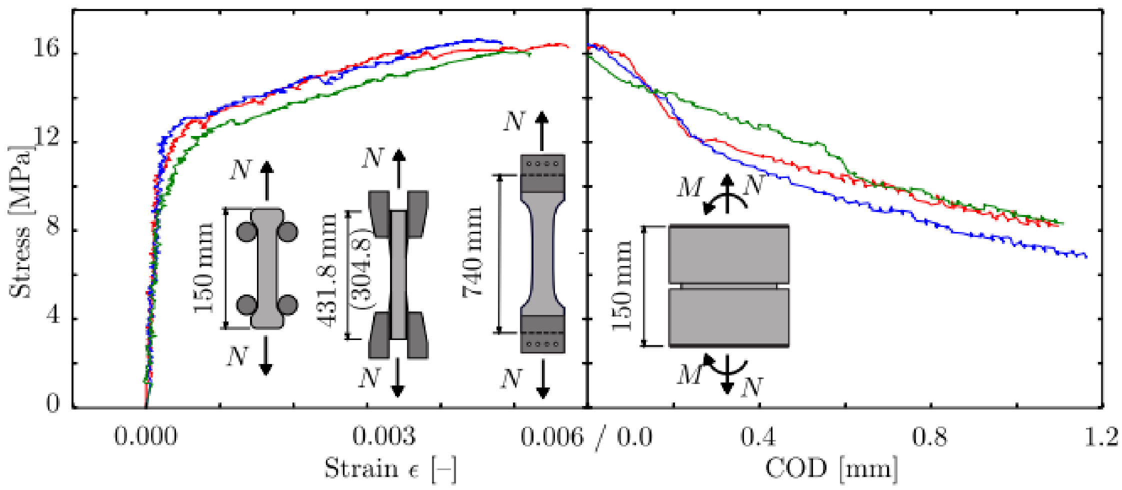

Figure 3: Combination of the freely rotating and fixed supports for the determination of the complete uni-axial tensile response

Figure 3 illustrates a procedure recommended by the authors. Both tests have been already applied by various researchers. The first test, which is suggested for the hardening part, has been used so far with dogbone shape-like specimens. The second test which is suggested for the softening part must avoid multiple cracking to assure the uniform crack opening and therefore:

$$\sigma_{pc} < \sigma_{cc} \frac{A}{A_{notched}} \quad (5)$$

RILEM TC 162-TDF [4] procedure is recommended for this part.

One of the main disadvantages of the freely rotating supports for the fiber-reinforced material is unintended bending which may occur after cracking due to unevenly distributed fibers. The disadvantage is eliminated by use of the notched specimen with the fixed supports. Such a setup assures relatively uniform crack opening.

Other advantages of the recommended procedure come from an overlapping of the hardening post-cracking response in the case of strain-hardening material. The overlapping allows controlling the measured values and also back-analyzing the crack spacing (s_{cr}) and number of cracks (n_{cr})

Notes:

In the case of strain-hardening materials, when the freely rotated setup is used up to the peak load (σ_{pc}), it is assumed that the local bending effects (in each crack) should eliminate themselves from a global point of view as multiple cracking occurs. Many cracks and randomness of the fiber distribution over the length of the specimen should provide a globally uniform response, regardless of possible bending within each crack. Consequently, the determined stress is smaller than the possible real stress which is a conservative assumption.

5. CONCLUSIONS

Experimental tests are crucial for determining material properties. Testing in compression is straightforward. By contrast, determination of uni-axial tensile properties is a difficult task. The most straightforward method is a uni-axial tensile test because it measures directly the desired properties.

Many test setups/methods can be found in the literature due to the lack of international consensus on a testing procedure for UHPFRC. The proposed tests were often difficult to perform and had a low reliability of results in terms of evenly distributed stresses over the cross-section and/or uniformly opened cracks. The main problems with performing uni-axial tensile tests are related to two origins: material (the localization and multiple-cracking of the tested specimen) and testing machines (the anchorage of the tested specimen).

When material localizes, a strain description of the response loses its informative capability (uniqueness) due to dependency on the measured length. The COD is used instead of the strain to describe the material behavior beyond its localization. However, the position of the crack is random and therefore notched specimens are often used to enforce the crack appearance within the measured area. Nevertheless, the artificial crack localization does not include randomness of the material and consequently overestimates material performance.

The anchorage of the tested specimens is a crucial factor for the proper performance of the uni-axial tensile tests. Imperfect connections can cause a premature failure or create unintentional stresses (e.g. bending due to misalignment). The anchorage itself significantly influences the measured values as it creates boundary conditions for the tested specimen (freely rotated and fixed supports). The difference of the measured material properties between two types of supports can be as high as 40%.

Uni-axial tensile testing of UHPFRC creates another issue due to a possible strain-hardening response. Consequently, the treatment of the localization and the anchorage aspects must be adjusted accordingly. The only one available norm for testing UHPFRC in uni-axial tensions fails in providing the correct elastic properties

The testing procedure for both strain-softening and strain-hardening materials is presented by the authors to cover the complete tension response of UHPFRC. The suggested procedure allows the complete description of material from the onset of loading up to the complete failure. It provides accurate and reliable data with advantages of simple and fast testing. The procedure combines two tests using the freely rotating and fixed supports:

- An un-notched specimen with a constant cross-section at the central part loaded by the freely rotating supports to capture multiple cracking and the realistic cracking strength;
- A notched specimen loaded by the fixed supports to capture the post-peak response.

The procedure eliminates non-uniform crack opening and also under- or over-estimation of the elastic properties. It allows controlling the measured values and back-analyzing the crack spacing and the number of cracks due to overlapping of the measured response. The presented example showed a possible simplification of the procedure by using only an un-notched specimen as Eqs. (1) to (3) proved sufficient accuracy.

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