THE GERMAN GUIDELINE FOR ULTRA-HIGH PERFORMANCE CONCRETE

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Abstract

In Germany, a guideline for UHPC is in progress and will be published by the German Committee for Structural Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb). The guideline extends and modifies the relevant European standards for design of concrete structures and concrete technology. After its implementation by the building authorities, the guideline is mandatory for structural applications with UHPC in Germany.

The guideline consists of two parts. Part 1 applies to the design of buildings and civil engineering works enabling structures exclusively reinforced with steel fibres, as well as pre-stressed and conventionally reinforced structures both in combination with steel fibres. Part 2 applies to concrete technology and quality control. It contains e.g. supplementary procedures and additional requirements for raw materials and for the mix design as well as control procedures enabling concrete producers to produce cost efficient UHPC mixtures based on regionally available raw materials for different applications.

Résumé

En Allemagne, une directive pour le Béton à Ultra Haute Performance (BUHP) est en cours d'élaboration et sera publiée par le comité allemand du béton (DAfStb). La directive modifie et étend les normes Européennes de conception, de produit et d'exécution du béton. Après sa mise en application par les autorités, la directive deviendra obligatoire pour les applications structurelles du BUHP en Allemagne.

La directive est composée de deux parties. La partie 1 porte sur le calcul des bâtiments et ouvrages de génie civil et couvre des structures exclusivement renforcées de fibres d'acier, ainsi que des structures précontraintes ou armées conventionnellement, en combinaison avec les fibres d'acier. La partie 2 porte sur la technologie du béton et le contrôle de la qualité. Elle contient par exemple des procédures et des spécifications supplémentaires pour les matières premières et pour la formulation ainsi que les procédures de contrôle qui permettent aux producteurs de réaliser des BUHP économiques basés sur les matières premières régionales pour différentes applications.

1. BACKGROUND AND SCOPE OF THE GUIDELINE

In Germany, so called Technical Guidelines form the basis for already tested but not yet frequently used and thus not yet standardised building materials and constructions. In case of cementitious materials and concrete structures, these guidelines are developed and published by the German Committee for Structural Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb). Background is often provided by European standards for design of concrete structures and concrete technology, namely EN 1992-1-1 [1] and EN 206 [2], which are officially implemented by the German building authorities. The guidelines become mandatory after their implementation by the building authorities.

The DAfStb-Guideline for Ultra-High Performance Concrete [3] is currently in draft. It applies to structures exclusively reinforced with steel fibres, as well as pre-stressed and conventionally reinforced structures both in combination with steel fibres. The concrete can be produced and processed at a precast factory or as ready-mixed concrete. The guideline refers to EN 1992-1-1 and EN 206 including the National Annexes for Germany of both standards. It is therefore structured likewise.

Part 1 of the guideline applies to the design of buildings and civil engineering works made with steel fibre reinforced UHPC. The verification procedures follow the design principles for reinforced and pre-stressed concrete, however they account for the special structural behaviour and high durability of UHPC. In this regard, modifications were made concerning e.g. stress-strain relationship, creep and shrinkage, required concrete cover, structural analysis, and recommended values of maximum crack width.

Design equations were modified or extended in order to account for the contribution of the fibres. Here, the post-cracking tensile strength, which is defined as the nominal axial concrete tensile strength transferred by the fibres in the cracked state, characterises the efficiency of the fibre reinforcement and serves as the main material parameter of the steel fibre reinforced UHPC. It is intended to determine the post-cracking tensile strength by establishing a 3-point-bending tensile test applying transfer factors to adapt to axial post-cracking tensile strength.

Part 2 of the DAfStb-Guideline for Ultra-High Performance Concrete applies to concrete technology and quality control. Different from other standards or guidelines established for UHPC, this part of the guideline also contains supplementary procedures and additional requirements enabling concrete producers to design and produce individual application oriented and cost efficient UHPC mixtures based on regionally available raw materials best fitting their production facilities. This comprises characterisation and quality assurance of cement, mineral additions, and superplasticisers, as well as optimisation of packing density of the finest grain up to 0.25 mm (see [4] and Table 1). Maximum grain size is specified between 0.5 mm and 16 mm, based on practical experience.

There are explanatory instructions for the optimal composition and workability of UHPC for different applications. A set of consistency classes specified in EN 206 will apply also for UHPC (including those for self compacting concrete). The tests of the fresh and the hardened concrete acc. to Series EN 12350 [5] and EN 12390 [6] will be extended for UHPC, especially with regard to reliable production and exact preparation of specimens [7]. A special annex of the guideline consists of rules for heat treatment of UHPC.

The technical content of the guideline is based to a large extent on the knowledge gained from an extensive multiannual coordinated research programme (German Priority Programme 'Sustainable Building with Ultra-High Performance Concrete'), which was conducted in

Germany between 2003 and 2013. It consisted of about 40 projects. The projects covered the whole spectrum from selection and characterization of appropriate regional raw materials, mix design and processing of material, its durability, structural behaviour in the ultimate limit states (ULS) and in the serviceability limit states (SLS), fitting technologies like gluing and anchoring as well as fire resistance and sustainability aspects. The full range of projects and their results are presented in [8]. In addition, several pilot projects were realised including e.g. bridges, roads, sewer pipes and other precast elements.

2. STRENGTH AND DURABILITY

The DAfStb-Guideline defines three strength classes C130, C150, and C175 (comparable to the French Standard NF P18-470 [9]) relating to the characteristic compressive strength in MPa obtained from cylinders with h/d [mm] = 300/150, which were stored under water until testing and tested acc. to EN 12390-2 [10] and EN 12390-3 [11]. Cylinders with h/d [mm] = 200/100 and cubes with a = 100 mm may be alternatively applied in initial and conformity tests in order to enable the use of machines with limited capacity. For both specimen sizes as well as for cubes with a = 150 mm, which also serve as standard specimen type acc. to EN 206, conversion factors for the compressive strength will be provided [12].

Factors highlighting the significantly improved durability of UHPC compared to normal-strength (NSC) or even high-strength concrete (HSC) are its considerably enhanced resistance to concrete corrosion as well as to corrosion of both steel fibres and conventional reinforcement. All tests performed in the laboratory as well as on UHPC-elements of the Gärtnerplatz-Bridge build in Kassel in 2007 [13] confirmed that the carbonation depth was below 1 mm after up to 15 years of artificial and/or natural weathering independent of the storage conditions.

With regard to chloride migration both the time-dependent progress as well as the absolute amount of chloride ions penetrating into the concrete is significantly reduced [14]. Together with an adjusted thickness of the concrete cover and an adequate limitation of crack width this higher resistance contributes to the challenge of more slender, material saving and thus more sustainable concrete structures made with UHPC.

The improved durability is reflected by the classification of UHPC with regard to the exposure classes acc. to EN 206. For the strength class C130 the rules for the exposure classes of EN 206 will stay unaltered due to the fact that this strength may be achieved even without a significant reduction of capillary porosity of the microstructure determining the resistance to harmful liquids and gases. For C130 the highest resistance class of each exposure is decisive. The strength classes C150 and C175 with a maximum w/c-value of 0.25 in combination with an optimised packing density of the fines will receive a bonus with respect to the impermeability of the microstructure and thus the increased physical and chemical resistance.

Presuming that cement with high sulphate resistance CEM I-SR 3 and/or with low C_3A content is used, additional protection, e.g. by epoxy-coatings, as foreseen in EN 206 for exposure class XA3 can be omitted in case that classification to XA3 was necessary due to pH-value or due to specific concentration of ammonium or carbon acid. A new performance class XA4 is defined for very strong chemical attacks by soils or groundwater with a pH-value down to 3.5 or for ammonium concentration of up to 1000 mg/l. This is applicable to highly dissociated acids. In case of slightly dissociated acids, the acid capacity should be likewise taken into account. Concerning this matter, EN 206 should be extended also to ordinary concrete. The improved chemical resistance of strength classes C150 and C175 provides the chance to produce e.g. sewage pipes and waste water structures, which are significantly more durable and thus more cost effective compared to those made of ordinary concrete [15].

Based on [16] and practical experience, UHPC assigned to strength classes C150 and C175 is practically insensitive to freeze-thaw attacks with and without de-icing agents. The maximum degradation of about 50 g/m^2 found for UHPC in the CDF-test is only about 3 % of the limit currently set for ordinary concrete designed for exposure class XF4 acc. to EN 206 (typically air entrained concrete).

Regarding abrasion resistance, UHPC again complies with the requirements set for very heavy duty loading (XM3), e.g. caused by floor transport vehicles with steel wheels on industrial floors.

The combination of improved chloride resistance, insensitivity to freeze-thaw attacks with and without de-icing salt, and high abrasion resistance makes UHPC the ideal material for highly trafficked continuously reinforced pavements. Comprehensive theoretical and laboratory research performed at the University of Kassel [17] showed that the load bearing capacity of a 150 mm thick reinforced pavement layer made with UHPC is equivalent to a 260 mm thick layer made with plain ordinary concrete – but its service life is about nearly twice as long. These findings were confirmed by practical experiences gained at heavily loaded test track pavements. UHPC pavements can be placed by common slipform-pavers or – e.g. for rapid repair purposes – by placing prefabricated elements on a mortar bed [18].

In order to determine the durability of UHPC against thermal loading up to 250 °C, the mixture M3Q used in the German Priority Programme 'Sustainable Building with Ultra-High Performance Concrete' has been analysed. Conventionally heat treated cubes with a = 150 mm were subjected to either one or five thermal cycles as shown in Figure 1.

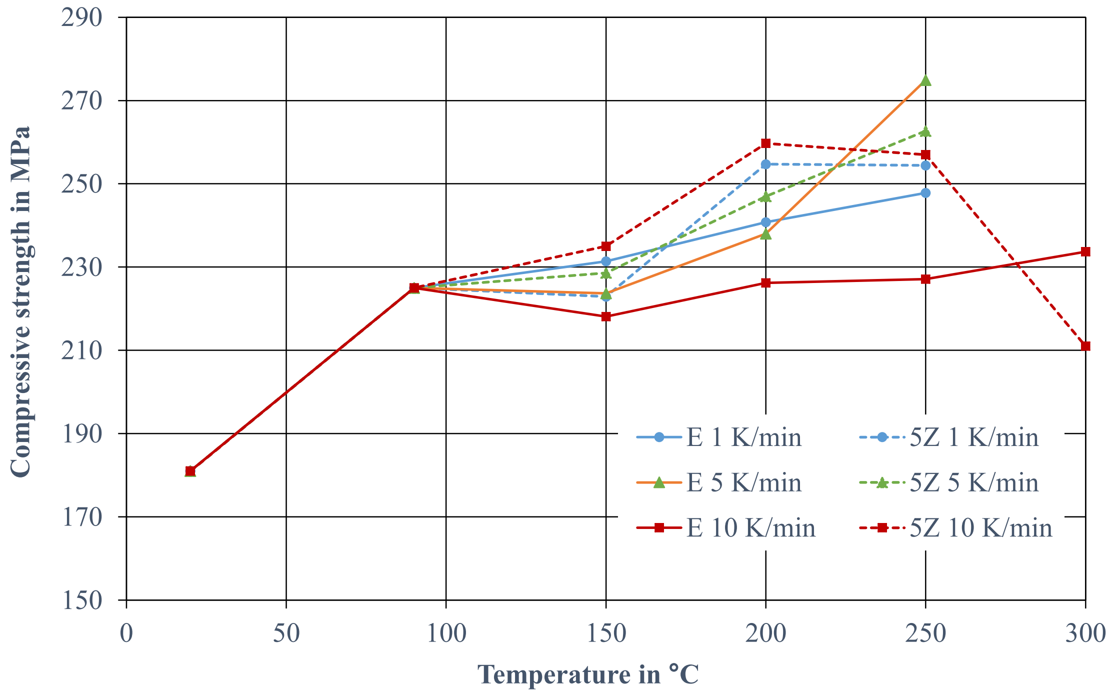

Figure 1: Compressive strength after thermal treatment at different temperatures and heating rates

The specimens were cast at 20 °C, demoulded after 24 hours, then cured for 48 hours at 90 °C and thereafter stored at 20 °C/65 % RH for cooling down. Then, they were thermally loaded at different heating rates of 1 to 10 K/min at temperatures of up to 300 °C (Figure 1: E – one cycle, 5Z – five cycles), restored at 20 °C and tested after 28 days. The UHPC resisted testing temperatures of up to 250 °C. The compressive strength was at least equal or higher compared to an untreated reference specimen. At 300 °C in combination with high heating rates cracks appeared and the strength dropped. Consequently, UHPC can be assumed to be thermally resistant to temperatures of up to 250 °C equivalent to ordinary concrete. In this regard, EN 206 can be applied to UHPC as already proposed in [19].

3. RAW MATERIALS, MIX DESIGN AND QUALITY ASSURANCE

The aim of the guideline is to enable individual concrete designers and producers to develop their own mix design for UHPC based on regional available raw materials optimised to cover the needs of the individual production and of the specific application. Practical experience confirmed that all consistency classes acc. to EN 206 and even no-slump UHPC for concrete blocks and waste water pipes can be developed based on the mandatory and explanatory instructions for optimal composition and workability provided by the guideline. In this regard, additional tests and requirements are necessary to precisely evaluate and to physically and chemically characterise the best fitting raw materials. Table 1 shows an excerpt of the quality assurance chapter of the guideline covering cement, mineral additives, silica fume or slurry, coarser aggregates and superplasticiser. In addition, a method is presented in order to improve the packing density of the finest grains up to 0.125 mm – being one basic criteria to make the microstructure denser and impermeable in order to achieve the strength classes C150 and C175 and, if necessary, to benefit from the improved chemical resistance as mentioned in chapter 2.

Based on the results of a comprehensive test programme performed within the framework of the German Priority Programme 'Sustainable Building with Ultra-High Performance Concrete', the test procedures commonly used to characterise the performance of fresh and hardened concretes where evaluated. They are principally appropriate for testing UHPC as well. In some cases the relevant European standards have to be specified in more detail, e.g. with regard to the preparation of the surface of compressive strength specimens or the procedure for casting the beams for bending tensile tests to get a uniform and reliable distribution and orientation of the fibres (see chapter 4). Further information on the testing issue including the precision of the test procedures may be found in [7]. A special annex of the guideline will provide a test procedure for validating the resistance to sedimentation of both the coarser aggregates and the steel fibres.

During production additional tests or an increased number of tests (compared to ordinary concrete) have to be performed to meet the specific challenges of UHPC, e.g. with regard to the larger number of ingredients, the more sophisticated composition and the greater sensitivity to deviations in water content and dosage of other ingredients. Due to the limited extend of this paper the quality assurance measures cannot be presented in more detail.

In a majority of the cases and especially when elements are prefabricated, hardened concrete is heat treated at about 80 to 90 °C to accelerate the strength development and to compensate the pronounced autogenous shrinkage. Different from ordinary concrete, the final compressive strength is not reduced but significantly increased by up to 25 % by an appropriate heat treatment. In order to avoid failures and to minimise the costs, detailed information about how to perform heat treatment is given in the guideline.

Table 1: Quality assurance for developing and controlling individual UHPC mixtures based on regionally available raw materials (excerpt from [3])

	Material	Examination
UH1	Cement	• Grain composition: proportion D_{15}, D_{50}, D_{95} (laser granulometry[1)]). • Water demand, fineness, Sulphate and C_3A-content (Series EN 196 [20]). • Consistency test of the concrete as in the initial test[2)]. • Retention of samples.
UH2	Admixtures	• Density, solids content, consistency test of the concrete as in the initial test, retention of samples.
UH3	Mineral additions	• Silica suspension: Density, water content, dry substance acc. to Series DIN EN 13263 [21], BET-surface acc. to ISO 9277[1)] [22] on silica fume in suspension, loss of ignition. • Silica fume: BET-surface, loss of ignition. • Blast-furnace slag and mineral flour: Grain size composition: D_{15}, D_{50}, D_{95} by means of laser granulometry[1)], loss of ignition, water content. • Consistency test of the concrete as in the initial test, retention of samples.
UH4	Aggregate	• Sieve test for each particle size group including elutriable material, check of grain shape, fines ≤ 0.25 mm and ≤ 0.50 mm, ignition loss fraction ≤ 0.5 mm.
UH5	Dry mixture of fines ≤ 0.5 mm (cement, mineral additions, aggregates)	• Packing density (void content dry mixture ≤ 0.5 mm): water demand acc. to Puntke (see Annex P.2 in [23]), reference: initial test.

[1)] Laboratory and test device to be stipulated. Device-specific deviations can occur in the test results.
[2)] Procedure to be stipulated in the individual case.

4. DESIGN PRINCIPLES

4.1 Scope and requirements on the steel fibres

The structure of Part 1 of the DAfStb-Guideline for Ultra-High Performance Concrete follows EN 1992-1-1. Most of the existing verification procedures could basically be retained. Where necessary, the design equations were modified or extended in order to account for the contribution of the fibres. The use of conventional reinforcement (rebars or tendons) is however obsolete for structures that fit one of the following conditions:

- the member is thin and predominantly loaded in bending,
- the tensile strength of UHPFRC is ignored when checking the equilibrium in ULS.

The conformity of the steel fibres used with UHPC has to comply with system "1" acc. to EN 14889-1 [24]. The shape of the fibres has to be straight and smooth without special geometrical anchorage. The fibres should have a length between 9 and 20 mm and a diameter between 0.1 and 0.4 mm. Tensile strength of the fibres should match with the fibre slenderness to guarantee fibre pull-out and to avoid rupture of a significant number of fibres.

4.2 Considering fibre contribution

For structural design, the post-cracking tensile strength f_{cft} is the most relevant material parameter of the steel fibre reinforced UHPC. It represents the nominal axial concrete tensile strength transferred by the fibres in the cracked state. The contribution of the uncracked concrete in tension is however ignored following the common philosophy of reinforced and pre-stressed concrete. The post-cracking tensile strength f_{cft} and its representative values (mean value f_{cftm}, characteristic value f_{cftk} (5 %-quantile), and design value f_{cftd}) are derived from bending tests. Geometry of the test specimens and execution of the bending tests are based on EN 14651 [25]. Evaluation of the tests and derivation of the post-cracking tensile strength however differ from the procedure that is given in EN 14651.

In order to obtain sufficient ductility and robustness, UHPC has to provide a minimum value of post-cracking tensile strength when used in structural applications. Thus, the DAfStb-Guideline defines a minimum value $f_{cftk,min}$ that may not be gone below, independent of the requirements for structural resistance or serviceability. In the current draft, $f_{cftk,min}$ is related to the compressive strength class, defining $f_{cftk,min} = 0.02\ f_{ck}$.

For some verifications in ULS, the design value of the post-cracking tensile strength f_{cftd} is the only parameter needed anyway and therefore is applied directly in the design model (e.g. verification procedures for shear, torsion, and punching).

For limitation of crack width in SLS, the stress-crack width relationship acc. to Eq. (1) is used to determine the appropriate value of the concrete tensile stress transferred by the fibres.

$$\sigma_{cf} = f_{cftk} \cdot \left(2 \cdot \sqrt{\frac{w_k}{w_0}} - \frac{w_k}{w_0} \right) \text{ for } w_k \leq w_0 \text{ ;} \quad \sigma_{cf} = f_{cftk} \text{ for } w_k > w_0 \tag{1}$$

In Eq. (1), σ_{cf} is the actual concrete tensile stress transferred by the fibres in the cracked state, f_{cftk} is the characteristic value of the post-cracking tensile strength, w_k is the actual crack width ($w_k = 0$ for the unloaded state), and w_0 is the crack width when reaching f_{cftk}.

Since experimental determination is difficult, w_0 may be obtained using Eq. (2).

$$w_0 = \frac{1.3 \cdot \tau_{fm} \cdot l_f^2}{E_f \cdot \phi_f} \tag{2}$$

In Eq. (2), τ_{fm} is the average bond stress between fibre and matrix, assuming a rigid-plastic bond law, l_f is the length of the fibre, ϕ_f is the diameter of the fibre, and E_f is the modulus of elasticity of the fibre (typically E_f = 200,000 MPa). τ_{fm} may be assumed to be equal 1.3 f_{ctm}, where f_{ctm} is the mean value of the tensile strength of plain UHPC.

In case of cross-sections subjected to bending, the contribution of the fibres is significantly affected by the interaction with the conventional reinforcement, which is however characterised by a stress-strain curve. Thus, for cross-sectional design in ULS both a special stress block is introduced in order to account for the fibre contribution and the stress-strain curve of reinforcement is modified (see chapter 4.3).

4.3 Modified design stress-strain relationships for concrete and reinforcing steel

For NSC and HSC, EN 1992-1-1 defines a parabola-rectangle diagram as stress-strain curve to be applied for design of cross-sections. For NSC, the shape of the ascending part of the stress-strain curve (square parable with $n = 2$), the strain at reaching the compressive strength (ε_{c2} = -2.0 ‰), and the ultimate strain (ε_{c2u} = -3.5 ‰) are kept constant for all strength classes. In contrast, the exponent of the parabolic function n and the strain at failure ε_{c2u} are assumed smaller with increasing strength class for HSC. The strain at reaching the compressive strength ε_{c2} is however increased continuously with increasing strength class until reaching ε_{c2} = -2.6 ‰ for C90/105. According to the German National Annex of EN 1992-1-1, this value is also used for the strength class C100/115.

Due to its small plasticity in compression, for UHPC a linear-elastic stress-strain relationship is assumed for design. This complies with an exponent of the parabolic function n = 1.0. Since evaluation showed, that the influence of ε_{c2} on the result of cross-sectional design is only marginal, the strain at reaching the compressive strength was defined for all UHPC strength classes (C130, C150, and C175) with ε_{c2} = -2.6 ‰, i.e. equal to the strength classes C90/105 and C100/115. A plastic range of the stress-strain curve that might be justified for heavy fibre reinforced UHPC was conservatively neglected.

Figure 2 shows the assumed stress distribution and the internal forces for the design of cross-sections. Aside from the steel tensile force F_{sd} and the concrete force F_{cd} resulting from linear stress distribution of UHPC in compression, the contribution of the fibres is considered by a stress block in the tensile zone.

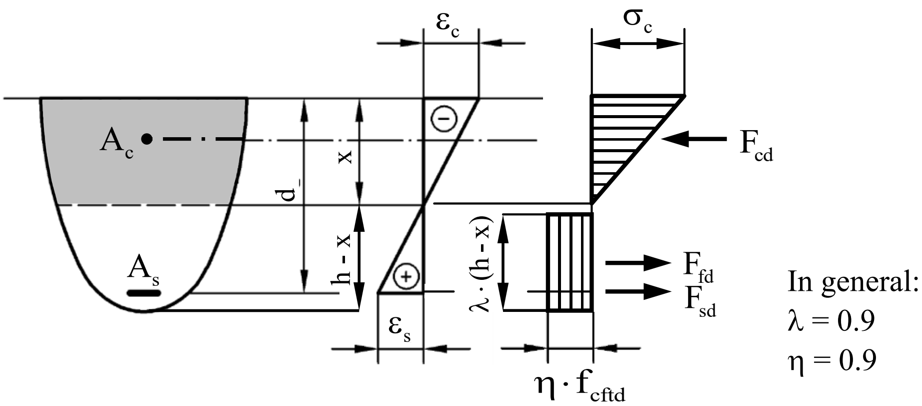

Figure 2: Assumption of stress distribution for the design of cross-sections [26]

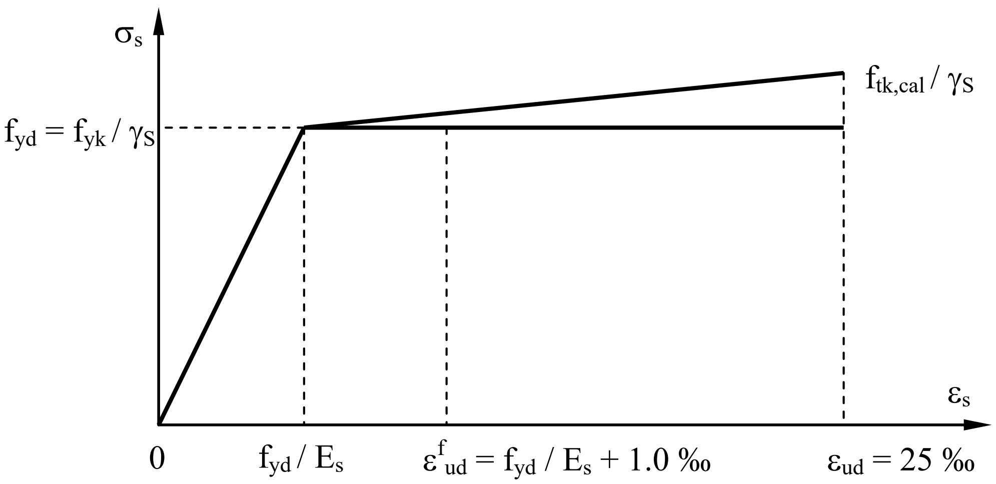

Figure 3: Modified design stress-strain diagram for reinforcing steel [3]

Since tests on heavy fibre reinforced members showed that the maximum axial loading (tensile member) or bending capacity (beam) is already reached immediately after the reinforcement's onset of yielding, a special limitation of the steel strain was introduced. If the fibre contribution is considered, a modified stress-strain curve with horizontal top branch and a strain limit $\varepsilon^{f}_{ud} = f_{yd}/E_s + 1.0$ ‰ is to be used (Fig. 3). Alternatively, the well-known stress-strain curve with inclined top branch and $\varepsilon_{ud} = 25$ ‰ may be used in cases where the contribution of the fibres is neglected when checking the structural resistance.

5. CONCLUSIONS AND OUTLOOK

The DAfStb-Guideline for UHPC is expected to be finished in 2018. It will extend the scope of application for concrete structures significantly. Based on the experience already gained with UHPC in practice, the highest strength class will currently be limited to C175, which will not be obstructive for the majority of applications. The strength class C130 is considered to form a link between HSC and typical UHPC, which is commonly defined by a strength of at least 150 MPa.

In order to benefit from the outstanding properties of UHPC, enhancements in structural design should not be constrained by restrictions of the codes. In this regard, extensions and modifications concerning design (e.g. enabling exclusively fibre reinforced structures) and concrete-technology were made, wherever justifiable. With regard to durability, new exposure classes are introduced for strength classes C150 and C175 in order to account for the increased chemical resistance. It seemed to be important for the editors of the guideline to enable cost efficient individual UHPC mixtures adapted to the specific application.

Since European standards do not cover the application of UHPC, in Germany a special approval by the German building authorities is currently required in each single case. The Technical Guideline of the German Committee for Structural Concrete will simplify this process, help improving the acceptance of UHPC as building material by the building owners and significantly extend the possibilities of using UHPC in structural applications.

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