Axial tensile strengths of UHPC and UHPFRC

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Abstract. UHPC and UHPFRC are remarkable materials which have properties with significant advantages. In addition to high compressive strength, they have higher tensile strength than conventional concrete. To study the tensile strength of UHPC and UHPFRC, a series of experimental programs have been developed at Kassel University. The effects on the fibre efficiency produced by varying the volume of the steel fibre percentage are discussed. When the results are compared to proposed equations generated in some European countries, the results are generally similar and confirmed satisfactorily. Satisfying justifications are also obtained when applied to the results for the axial tensile strength of the UHPFRC specimens. By using the proposed equations, the fibre’s effective (efficiency) stresses in UHPFRC in the stages of fibre activation and pullout can be calculated. However, not all the results of this study can be confirmed by other countries (e.g. USA, Japan). Diverse circumstances taking place during the production of the material may have to be taken into account to explain the dissimilar output. Studies of the tensile strength of UHPC and UHPFRC are important, with the aim of supporting more documentation for the development of recommendations, guidelines, standards and norms; thus meeting the needs of structural design.

1. Introduction

In 2007, the first European UHPC (Ultra High Performance Concrete) composite pedestrian bridge was constructed across the Fulda River, in Kassel, Germany [1]. The bridge has a deck thickness of 8–12 cm and a 140 m span steel space frame. Developed by Kassel University, the bridge was designed to hold a pedestrian load of 60 kN / 6 Ton (figure 1). As an advanced form of conventional concrete (normal concrete, high strength concrete), UHPC has significantly enhanced properties. When fibre is added to its composition, UHPC is referred to as UHPFRC (Ultra High Performance Fibre Reinforced Concrete). The addition of fibre significantly increases the strength and durability of UHPC. Besides the fact that it is considered to have a very high compressive strength, which is ≥ 150 MPa, current research shows that UHPFRC is also believed to have a high tensile strength, having a value that may reach 15 MPa [2]. The high tensile strength in UHPC/ UHPFRC is significant, as they have superior properties compared to conventional concrete, and it also leads to higher ductility, leading to the possibility of eliminating the need for reinforcement (i.e. bars, wire, mesh) with the consequent
flexibility in expanding the applications of UHPC to a wider range of structural shapes and forms [3, 4]. The UHPFRC’s enhanced properties contribute to the total performance of the structure, improve construction safety, offer a longer service life, and lower maintenance costs. The available recommendations and guidelines have led to the use of UHPC/ UHPFRC in some research and structural applications. However, the available literature has not always received satisfactory confirmation when comparing the results of some investigations. The reasons for this need to be determined. Thus, this study aims to investigate the tensile strength of UHPC and UHPFRC. The available literature is employed, to clarify the results.

![Image](Figure 1. Gärtnerplatzbrücke, Kassel, Germany [1].)

2. Current recommendations and guidelines

The development of the recommendations for UHPC, from the stage of drafting until the current progress, has needed a gradual process and some years. Starting in France, in 2002, the first technical recommendation of UHPC was published, addressing UHPC’s properties and structural designs [5]. In 2003, Germany published some state of the art reports of UHPC discussing its material and structural design aspects [6-8]. Japan, in 2006, published a draft recommendation for the design and construction of UHPC [9]. In the USA, in 2013, there were published guidelines for the use of UHPC for bridge structures, covering the research, development and applications of UHPC [10]. Other countries have used UHPC in structural designs by bridging the available recommendations, guidelines and research findings for UHPC with those for conventional concrete. Some of these countries include Switzerland, Austria, Italy, the Netherlands, Slovenia, Canada, Australia, New Zealand, South Korea and Malaysia.

3. UHPC and UHPFRC

3.1. Principles for the making of UHPC/ UHPFRC

For improving the high strength and durability in the production of UHPC, the following principles should be considered in the production process of UHPC/ UHPFRC: 1) use a very low water–cement ratio, resulting in a very dense matrix for the specimens; 2) use fine particles for gaining a high and compact density of material; 3) adjust the workability by using a high amount of effective superplasticizers; and 4) increase tensile and shear strengths, making UHPC more ductile, by introducing fibre.

3.2. Fibre in UHPFRC

UHPC is brittle. Thus, to improve its ductility, as well as its tensile and flexural capacities, a variety of types and amounts of fibre are added to its composition. Different types of fibre can be used, e.g. steel fibre, plastic fibre, glass fibre, micro fibre. According to Leutbecher, in order to optimize the fibre effectiveness, the ratio between the fibre length and the maximum aggregate particle size used in the UHPFRC is suggested to be at least 10 [11]. The optimum length of the fibre used should be in the range of 8–16 mm, with a diameter in the range of 0.08–0.5 mm (the optimal mean diameter used is in the range of 0.1–0.2 mm) [12]. The Japanese recommendations mention that in order to achieve a
targeted reinforcement effect and a homogeneous spread of the fibre in the UHPFRC mixture, the standard fibre used in UHPFRC should be: 10–20 mm in length, 0.1–0.25 in diameter, tensile strength \( \geq 2 \times 10^3 \) MPa, and account for 2 vol.-\% fibre in the composition [9].

The use of steel fibre with a length of 13 mm, a diameter of 0.15 mm, at an amount of 2–2.5 vol.-\% fibre has provided ductile behaviour to UHPFRC structures. UHPFRC which contains short fibres and is heat treated to \( \geq 250^\circ \)C shows enhanced mechanical performance both in compressive and tensile strength, however its fracture energy is reduced [13]. Compared to other types of fibre, steel fibre is specially fit to improve the ductility of UHPFRC in a post-cracking stage, and the use of polypropylene fibre 0.3–0.6 vol.-\% significantly increases the fire resistance of UHPFRC structures. Considering the the workability of fresh UHPFRC, attention to the necessary amount of fibre to add is required [14, 15].

3.3. Tensile stress–strain behaviour

UHPFRC’s tensile strength values are generally higher than that of UHPC, due to the addition of fibre to the UHPC. Unlike UHPC, which may suddenly fail after its first crack, UHPFRC exhibits sustained tensile strength after the specimen reaches its first crack [10]. Figure 2 illustrates a proposed idealized tensile stress and strain relation of UHPFRC, based on the material’s pre- and post-cracking responses during the strain hardening phase.

![Idealized uniaxial tensile stress vs strain relation of UHPFRC](image)

Based on some experimental researches at Kassel University, Fehling et al. [7, 8, 12, 16] has some approaches to the topics of UHPFRC tensile stress, strain and crack opening relations. For calculating the tensile strength of UHPFRC related to its characteristic compressive strength, Schmidt et al. [7] has proposed the equation.

\[
 f_{ctm} = 2.12 \ln \left( 1 + \frac{f_{ck}}{10} \right) \quad (1)
\]

where in \( f_{ctm} \) is the tensile strength (N/mm\(^2\)) of the UHPFRC and \( f_{ck} \) is its characteristic compressive strength (N/mm\(^2\)). While, for predicting the tensile strength of high strength concrete related to its characteristic compressive strength, DIN 1045-1 [14] has mentioned.

\[
 f_{ctm} = 0.3 \times (f_{ck})^{2/3} \quad (2)
\]

where in \( f_{ctm} \) is the concrete’s tensile strength (N/mm\(^2\)), \( f_{ck} \) is its characteristic compressive strength (N/mm\(^2\)) and \( f_{ck} = f_{ck,0.05} = 0.7 \times f_{cum} \). For UHPFRC crack opening and tensile stress stress relations, the following curves are proposed (see figure 3), wherein the falling branches have various slopes, depending on the characteristics of the used fibre content.
Further findings of these researches result in the relations between the UHPFRC matrix tensile strength and fibre efficiency (figure 4), and the superposition of matrix softening and fibre activation (figure 5). The matrix tensile strength is taken from results for notched prisms, while the fibre efficiency represents the maximum tensile stress carried by the fibre after cracks.

The following equations are used for approximating the stress–crack-opening relation of UHPFRC in the stage of fibre activation and fibre pullout [6, 8, 17, 18].
Fibre activation:  
\[ \sigma_{cf} = \sigma_{cf0} \left( 2, \sqrt{\frac{w}{w_0}} \right) \]  
(3)

Fibre pullout:  
\[ \sigma_{cf} = \sigma_{cf0} \left( 1 - \frac{2w}{w_f} \right)^2 \]  
(4)

where in
- \( \sigma_{cf} \) effective stress in fibre-reinforced concrete at crack (N/mm²)
- \( \sigma_{cf0} \) fibre efficiency calculated as a design value, \( \sigma_{cf0} \) to analyse the ultimate limit state (N/mm²)
- \( w \) current crack width (mm)
- \( w_0 \) crack width upon reaching fibre efficiency (if experimental measurements unavailable, in mm)

4. Investigation

4.1. Specimens and tests

A series of UHPC and UHPFRC prisms having a cross section of 40 mm x 40 mm and length of 80 mm, notched in the middle of the prism having width x depth = 5 mm x 5 mm, were tested at the age of ± 28 days. The notch in the middle of the prism is made to localize the local stress concentration (failure). UHPC mixture Type M3Q-210 was used in this axial tensile test, developed by the Official Building Materials Testing Institute (AMPA, Amtliche Materialprüfanstalt für das Bauwesen) in cooperation with the Chair of Building Materials at Kassel University. The UHPC mixture was designed to have a variety of fibre percentages by volume, namely: 0, 1 and 2 vol.-% fibre. Prior to testing, specimens were cured under room temperature of 20°C–23°C, beginning on the second day after the specimens were taken out of their moulds. In each variable of UHPC/ UHPFRC having a variety of percentages of fibre, 6 testing specimens of UHPC prisms were investigated. The steel fibre in the UHPFRC is identified to have lengths of 10 mm and diameter of 0.2 mm.

Figure 6. The axial tensile test setup, specimen and instrumentation.

The axial tensile test was conducted under an increasing load until failure, using RBO2000, a universal testing machine having a maximum load of 1.6 MN. The RBO2000 machine provides a variety of loading rate speeds; a rate speed of 0.01 mm/sec is used to test UHPC specimens, while
0.05 mm/ sec is used to test UHPFRC specimens. However, when the displacement of specimens shown by all transducers had reached 2 mm, the initial rate speed was increased by changing it from 0.01 to 0.05 mm/ sec. The tensile test setup, specimen and instrumentation are shown in figure 6. The test configuration is installed to ensure that loading forces are applied without eccentricity, and deflection data are recorded through transducers.

4.2. Results and discussion

The result of the experimental investigation in this study are summarized in figure 7, in terms of tensile stress and crack opening relations. From the experimental results, it is identified that the UHPC/ UHPFRC in this study have mean maximum axial tensile stresses of 2.44 MPa (UHPC 0%), 5.32 MPa (UHPFRC 1%), and 7.30 MPa (UHPFRC 2%). These mean experimental results of the axial tensile strength values (achieved at max. crack), are closer to the analytical results calculated with equations (3) and (4), proposed by Fehling et al. [12, 16], in the stage of fibre pullout, namely: 2.44 MPa (UHPC 0%), 5.32 MPa (UHPFRC 1%), and 6.91 MPa (UHPFRC 2%). The similarity of these results may have come about as the equations are developed in Kassel University, the same place where this study was conducted. It may be a consequence of the similarity of the factors and conditions applied and used. When compared to results gained by using equation (1) from Schmidt et al. [7] and equation (2) from DIN 1045-1 [19], the analytical results are close only when applied to UHPFRC (UHPC with fibre), namely: 6.24 MPa (based on equation 1) and 7.70 MPa (based on equation 2) - for UHPFRC 1% (1 vol.-%), and 6.23 MPa (based on equation 1) and 7.71 MPa (based on equation 2) - for UHPFRC 2% (2 vol.-%). This may have happened as these equations are designed for calculating the tensile strengths of UHPFRC (UHPC with fibre) and high performance concrete. It is very interesting that these equations are based on investigations located in Germany and other European countries. Other results of this study, by calculating using equations (3) and (4), in terms of the fibre’s effective (efficiency) stresses in UHPFRC in the stages of fibre activation and pullout are 0.85 MPa (UHPC 0%), 1.08 MPa (UHPFRC 1%), and 7.30 MPa (UHPFRC 2%) – in the stage of fibre activation, and 2.44 MPa (UHPC 0%), 5.32 MPa (UHPFRC 1%), and 6.91 MPa (UHPFRC 2%) – in the stage of fibre pullout.

From figure 7, it can be seen that the specimens’ response is linear until the first crack occurs. The first cracks are defined by a decrease in tensile stress. Afterward, the tensile stress begins to increase. The sawtooth pattern in the curves indicates the forming of additional individual cracks throughout the region of highly concentrated tensile stress of the prism, which is located in the notch. This behaviour is in line with the analysis of the FHA (Federal Highway Administration) in the USA [10].

By considering the curve’s shape after the maximum axial tensile strength is achieved, it can be said that the amount of fibre added improves the ductility of the UHPFRC matrix. The improved ductility especially is shown significantly in the post-cracking stage, by the appearance of smooth gradual failure (comparison of the curves between UHPC 0%, UHPFRC 1% and UHPFRC 2%). This behaviour is in line with the findings of many investigations. Some fibre parameters which influence the increase of post peak behaviour are: fibre’s volumetric ratio, fibre’s geometric properties, fibre’s length to aggregate size ratio, the bond characteristic between fibres and UHPC matrix, fibre’s stiffness, fibre’s orientation, etc.

4.3. Results compared to other recommendations/ guidelines

According to the FHA of the USA and referring to other findings, it is found that the UHPC’s axial tensile strength values are in the range of 6–10 MPa [10, 16]. The JSCE (Japan Society of Engineers) guidelines mention the use of UHPFRC 2 vol.-%’s tensile strength value of 9 MPa [9]. According to the SETRA/ AFGC recommendations of France, for the design values, it proposes the use of axial and flexural tensile strength values of 8 and 8.1 MPa, respectively [5]. However, according to other findings (research), compared to UHPC, the UHPFRC tensile strength value is in a varied range of 7–15 MPa.
It is interesting that the mean experimental results of the axial tensile strength values (achieved at max. crack) found by this study, namely 2.44 MPa (UHPC 0%), 5.32 MPa (UHPFRC 1%), and 7.30 MPa (UHPFRC 2%), are less than the values proposed by all recommendations, except for the axial tensile strength values of UHPFRC 2 vol.-%, namely 7.30 MPa: this mean value is in line with the FHA’s report (in the range of 6–10 MPa) and the values found in other research (in the range of 7–15 MPa).

It is found that among specimens UHPFRC 1% (from Round A to C), the axial tensile strength values are varied. The mean value of Round C is in line with the FHA report’s value, which is in the range of 6–10 MPa [10, 16]. These differences in the axial tensile strength may be generated through:
a) different materials, constituents and compositions of UHPC/ UHPFRC, b) different homogeneities and compactions of the UHPC/ UHPFRC matrix, c) different shapes and sizes of the mould of UHPC/ UHPFRC specimens, d) different types, volumes, dimensions, spreads of the fibre, e) different procedures for putting the fibre in the UHPC/ UHPFRC matrix, f) different types and procedures for the production of UHPC/ UHPFRC, g) different types and procedures of treatment, h) different room temperatures, weather conditions, etc.

5. Conclusion
This study reports the results of an investigation of the tensile strength of UHPC/ UHPFRC prism specimens. When the results are compared to proposed equations generated in Germany, there is a prevailing similarity, and they are confirmed satisfactorily, especially for the axial tensile strength results of UHPFRC. However, not all the results of this study can be confirmed by recommendations and guidelines from other countries, such as the USA, Japan and France. Diverse circumstances take place during the production and testing of the specimens, which may account for the dissimilar results. In order to get a standard/ universal equation for the design calculation of UHPC/ UHPFRC elements, intensive investigation needs to be conducted. Cooperation between countries for developing investigations with the crisscross technique is recommended.

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