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Tensile Postcrack Behavior of Steel Fiber Reinforced Ultra-High-Strength Concrete

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Synopsis: Approximately 30 direct tensile tests have been performed on so-called Compresit matrix. This matrix is based on micro silica particles compacted in between the cement particles. The dense matrix, which shows high brittleness, is provided with ductility by means of steel fibers mixed randomly with respect to both position and orientation. Compressive strengths reaching 200 MPa are experienced with this particular matrix.

The fiber reinforcement index $V_f\,(L_f\,/d_f)$ is varied throughout the test series by means of three different fiber geometries and contents. Beside a plain mix without any fibers, the fiber reinforcement index is varied from 0.9 to 3.6, which is a wide range compared to other fiber reinforced concrete investigations.

The test results consist of measured bridging stresses versus crack widths after the initiation of the first crack. A micro-mechanical model developed by V.C. Li et al. is evaluated and compared to the results. This model agrees with low and moderate contents of both steel fibers and synthetic fibers.

It is concluded that the micro-mechanical prediction does not seem to be sufficient to model the post-crack behaviour of high-strength matrix reinforced with high amounts of steel fibers. However, the post-crack strength provided by the fibers crossing a crack plane is modelled satisfactorily.

Keywords: Ductility; fiber reinforced concretes; high-strength concretes; strength; tension tests

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INTRODUCTION

Among the high-performance concrete materials, that are being developed and investigated at present, fiber reinforced concrete (FRC) is of high interest. Adding fibers to concrete mix is widely used in order to extend its properties concerning cracking and energy dissipation, while the effect on the strength is limited. Thus it seems logical to apply fibers to high-strength concrete in order to increase its ductility, e.g. to reduce the risk of spalling followed by sudden collapse. However, the cost of fibers is often relatively high compared to the matrix material and therefore an optimization of the fiber content is needed.

The present paper is concerned with a high-strength concrete matrix reinforced with a high content of steel fibers. The fibers are primarily utilized to counteract the high brittleness of the matrix. The scope of the paper is to present direct tensile test results with this material and to evaluate a well-known micro-mechanical model to predict the tensile behaviour of FRC. This model and other related models are typically verified at relatively low fiber contents, or using low-stiffness fibers such as polypropylene. The improved mixing techniques and the development of efficient dispersing agents make it possible now to add considerably more fibers than before. Therefore, it is interesting to apply the models on these new FRC's containing many steel fibers.

In [1] a trade-off between tensile strength and ductility for these new FRC's is investigated. The high-strength matrices are mainly governed by dense particle systems (e.g. by means of micro silica) which are known to improve the interfacial fiber-matrix bond strength remarkably. However, these matrices also show increased brittleness which makes it difficult (almost impossible) to provide them with satisfactory pseudo-ductility by means of fibers. Therefore, it is concluded by Wu and Li [1] that, even though the matrix interfacial bond strength is increased considerably, its increased brittleness is too high to ensure pseudo-ductility when low aspect ratio (= L_f/d_f), high-stiffness fibers such as steel fibers are applied.

The term "pseudo-ductility" denotes the condition, where the fibers, crossing an open crack, still provide increasing stress transfer. If this so-called bridging stress increases beyond the matrix cracking strength, the stresses transferred back into the matrix may cause it to crack again, which is termed multiple cracking. These principles are treated for aligned fibers by Aveston and Kelly in the early seventies by means of the law of mixtures, i.e. an elastic analysis, see [2]. A micro-mechanical model which is adopted in the present analysis to treat multiple cracking is given by Li and Leung [3].

Description of Fiber Reinforced Compresit Matrix

The name Compresit is from compact reinforced composite and covers an ultra high-strength, steel fiber reinforced concrete mix which is additionally reinforced with conventional steel bars for structural use. The term "compact" refers to the conventional reinforcement, while the term "composite" represents the steel fiber reinforced matrix. The Compresit concept is patented by Aalborg Portland Cement Factory, Denmark, and it is closely related to the binder product Densit®.

The principles leading to both Densit and Compresit are described by H.H. Bache, see [4] and [5]. The matrix is densified by means of micro silica, which leads to water/binder ratios below 0.2 and it shows compressive strengths from 140 to 200 MPa. In order to increase the ductility of this Densit-based matrix, high amounts of short, randomized, steel fibers are added to the matrix. For Compresit matrix fiber contents up to 10 % are possible to mix satisfactorily (usually 6 % by volume is applied).

The steel fibers usually applied to Compresit matrix are straight Dramix® fibers with the geometry $d_f \times L_f = 0.4 \times 12$ mm ($\sigma_{fu} = 1350$ MPa), but 0.15 × 6 mm fibers ($\sigma_{fu} = 2950$ MPa) are sometimes utilized. In order to ensure proper distribution of the fibers and to allow for compact spacing of the conventional steel bars, the maximum aggregate size is only 4 mm. However, in the present analysis only fiber reinforced Compresit matrix is investigated, i.e. no steel bars are applied.

THEORETICAL BACKGROUND

The effect of fibers in cementitious materials is most pronounced during cracking. The fibers that cross a crack still transfer stresses even though the crack is significantly open. In a deformation controlled uniaxial tension test, the complete bridging stress - crack opening (σ_B - w) relationship may be observed after the deformations localize in a crack. The area under this curve equals the fracture energy G_F of the material. The initial part of the σ_B - w curve includes both a decreasing aggregate interlock and an increasing fiber debonding stress. After the fibers are debonded along their shortest embedment length, they start to slip out of the matrix under decreasing stresses. The possibility of fiber rupture is governed by the critical fiber length $L_{cr} = 0.5 d_f \sigma_{fu} / \tau$.

Fiber Bridging Stress

Here we shall adopt a simple micro-mechanical shear lag model to predict the behaviour of a fiber being pulled out of a matrix material, see [6]. The behaviour of a single fiber is transferred into a continuum by means of statistical methods, where the position and the orientation of a fiber is assumed to be uniformly distributed. The bridging stress originating from the fibers is given analytically as a function of the crack width:

$$\frac{\sigma_f}{\sigma_{pc}} = \begin{cases} 2\sqrt{\dfrac{\hat{w}}{\hat{w}^*}} - \dfrac{\hat{w}}{\hat{w}^*}, & 0 \leq \hat{w} \leq \hat{w}^* \\ (1 - (\hat{w} - \hat{w}^*))^2, & \hat{w}^* \leq \hat{w} \leq 1 \end{cases} \tag{1}$$

where the hat (^) symbolizes crack widths w, that are divided with half the fiber length ($\hat{w} = 2w/L_f$). The normalized crack width $\hat{w}^*$, corresponding to the peak of the σ_f - w relationship, and σ_{pc} are defined as

$$\hat{w}^* = \frac{2\tau}{(1+\eta)E_f} \frac{L_f}{d_f}, \quad \sigma_{pc} = \frac{g\tau}{2} V_f \frac{L_f}{d_f}, \quad \eta = \frac{E_f}{E_m} \frac{V_f}{1-V_f} \tag{2}$$

where g is the so-called snubbing factor (≥ 1) which takes into account that the pull-out strength of a single fiber increases when it is inclined to the crack plane normal. In Figure 1, the expression in (1) is outlined qualitatively. It should be noted, that a basic assumption for (1) is $\hat{w}^* \ll 1$, see [6]. This assumption is violated in Figure 1 of illustrative reasons.

Figure 1 also outlines the fracture energies due to fiber debonding and pull-out as areas under the σ_f - w curve. The debonding energy is calculated by integrating (1) from 0 to $\hat{w}^*$, giving $G_{deb} = 5\sigma_{pc} w^*/6$ and the pull-out energy is $G_{pull} = \sigma_{pc} L_f/6$.

Because of the assumption $w^* \ll L_f$, it is clear, that G_{pull} is much higher than G_{deb}. Therefore the fracture energy G_F of FRC is often modelled as pure pull-out energy because this part is dominant.

Equation (1) is based on the assumptions that debonding happens under the bond strength τ which is also the frictional resistance against pull-out. The surrounding matrix deformations are included through η. However, the simple analytical expressions (1) and (2) are due to $\hat{w}^* \lll 1$ which again demands small fiber-matrix stiffness ratios and/or small fiber contents. For steel fibers, where E_f/E_m typically ranges from 5 to 10, the fiber content should not exceed 1-2 % in order to fulfil the assumption. For soft fibers such as polypropylene, where E_f/E_m is below 1, much higher fiber contents are possible without violating the assumption. In [7] the micro-mechanical model is verified by means of direct tensile tests on FRC with small amounts (< 3 %) of both steel fibers and polypropylene fibers.

Pseudo-Ductility

In [3], a linear-elastic fracture mechanics model is proposed to predict the conditions for multiple cracking of FRC. The main condition is that the post-crack strength σ_{pc} exceeds the cracking strength σ_{cr} of the matrix, see also [9]. Furthermore, a so-called steady-state cracking condition is given which corresponds to a crack propagating under constant tensile stress because of the bridging fibers. If the latter condition is assured, the possibility of multiple cracking is also present. In [3], the steady-state condition has the form

$$G_{deb} \geq 10G_{tip} \tag{3}$$

where G_{tip} is the critical fracture energy provided to propagate a crack in the plain matrix material without fibers. The occurrence of steady-state cracking results in a material that is insensitive to initial micro-cracks, i.e. no sudden load-drop at first cracking.

The debonding energy G_{deb} depends on the crack width w^* and σ_{pc} (cf. (2) and Figure 1). Equation (3) can be rewritten into a lower limit for the fiber content which gives the so-called critical fiber volume V_f^{crit}. However, because of η in (2), the crack width w^* decreases with increasing V_f and the debonding energy G_{deb} increases with V_f from zero to its local maximum at the content V_f^{max}. Then G_{deb} decreases towards zero, when V_f is increased beyond V_f^{max}. The fiber content at which the maximum debonding energy occurs is calculated to equal $V_f^{max} = (\sqrt{(E_f/E_m)} - 1)/(E_f/E_m - 1)$. In the case $E_f = E_m$ the solution yields $V_f^{max} = 50$ %.

If the right-hand side of (3) is higher than the value of G_{deb} corresponding to V_f^{max}, then the satisfaction of (3) is impossible. Otherwise, a lower limit V_f^{crit} exists in order to fulfil the equality sign of (3).

In case of fibers with low stiffness and high aspect ratios, the fulfilment of (3) is obtainable in practice, see [1] and [3]. In case of steel fibers mixed into high-strength matrices where G_{tip} typically equals 100-200 N/m, the demands for the aspect ratio or the bond strength in order to fulfil (3) are not obtainable, see [1]. Thus the increased strength (and brittleness) makes steady-state cracking unattainable from a theoretical point of view. Reference [1] includes a few examples of this situation.

DIRECT TENSILE TESTS ON COMPRESIT MATRIX

In [8], a direct tensile test method, which is developed at Danish Technical University, is described. A FRC prism (50 × 50 × 40 mm) is glued onto two steel blocks which are bolted to a 250 kN Instron test machine. The test is strain-controlled by means of two extensometers measuring across a saw-cut notch. The rigid steel block connections ensure pure crack opening without rotation, i.e. the crack surfaces are separated parallel to each other during a test. Unfortunately the test prisms prepared without any saw-cut notch were not successful. Thus, all observations are based on notched specimens.

In the present test series, a total of eight different Compresit mixes are tested with at least four repetitions for each mix. In Table 1, the fiber contents and the fiber geometries for these mixes are given. The fiber contents range from 3 to 9 % besides a plain Compresit mix without fibers. This gives an experimental range of the fiber reinforcement index $V_f(L_f/d_f)$ from 0.9 to 3.6. For conventional steel fiber reinforced concrete, $V_f(L_f/d_f)$ = 1-2 is often given as a practical upper limit for what is possible to mix in practice.

The registered stress-strain relationship follows an ascending branch which is almost linear until cracking starts. For mix A without fibers, the stresses drop almost immediately to zero after cracking. For small fiber contents (3 %), a small load-drop is registered at first cracking as the fibers take over the matrix stresses followed by increasing bridging stresses until complete debonding and fiber pull-out. For higher fiber contents, the typical stress-strain curve only indicates a slight disturbance, at first cracking without any decided load-drop, which is followed by fiber debonding and pull-out. In order to perform comparisons between the different mixes, each observed stress-strain relationship is composed into a σ_B - w relationship after the first crack occurs. This is due to the assumption that all deformations after cracking are localized in a single crack. Thus, the post-crack strains are multiplied by the extensometer measuring length (12.5 mm) to obtain crack widths and the elastic deformations of the uncracked part of the specimen are subtracted.

Test Results

For each mix the experimental scatter is rather high. The post-crack strengths show coefficients of variation from 10 to 30 % which make any precise conclusions difficult. In Figure 2 and 3, some examples of the recorded σ_B - w relationships are shown and in Figure 4, four test repetitions are given to indicate the scatter. It should be noted that the bridging stresses are normalized with respect to the cracking strength σ_{cr} of the matrix in each case. The matrix cracking strength is only slightly influenced by the fibers and a constant value of σ_{cr} = 7 MPa is a good estimate. Thus, the cracking strength of the fiber reinforced matrix is basically identical to that of the plain matrix. The final crack width of 2.5 mm in Figures 2-4 is due to the maximum opening capacity of the extensometers.

As it appears from both Figure 2 and 3, the post-crack strength of mixes with fiber reinforcement indices higher than approximately 1 exceed the cracking strength. If the theoretical model of (2) where σ_{pc} is directly proportional to the fiber reinforcement index $V_f\,(L_f/d_f)$ is applied to the Compresit strengths, we find an effective bond strength $\tau^* \approx 6$ MPa where τ^* corresponds to $g\tau/2$ in (2). No single fiber pull-out tests exist on Compresit matrix, thus the correct value of τ is unknown. A slight difference in τ^* is observed between the fiber types, but the experimental scatter is too high for making any discrimination.

From Figure 2 and 3, it is clear that the aggregate interlock indicated by mix A vanishes very quickly. Therefore, the post-crack behaviour for crack widths exceeding 0.05 mm is governed by the fiber bridging stresses σ_f, whereas σ_B for small crack widths is composed of both the fiber bridging stresses and the aggregate interlock. The experimentally determined crack widths of the post-crack strength does not seem to follow the theoretical w^* from (2). By inserting typical Compresit parameters into (2), we get a theoretical value of $w^* \approx 5$ µm while the observations are at least one order of magnitude higher. A plausible explanation could be that the measurements include inelastic deformations outside the notched crack plane, i.e. the energy dissipation is not solely originating from a single crack plane as assumed.

DISCUSSION

From the test results depicted in Figure 2 and 3, it seems justified that the conditions for both multiple cracking and steady-state cracking are present for Compresit matrix. The post-crack strength is found to exceed the matrix cracking strength σ_{cr} at $V_f(L_f/d_f) \approx 1$, and this value of the fiber reinforcement index also seems to be the lower limit for steady-state cracking. Thus, when $V_f(L_f/d_f)$ exceeds 1, the first cracking is not followed by a significant load-drop. However, if a theoretical solution to (3) is sought, no answer seems to exist.

In [1], a Compresit-like material is treated. The bond strength τ is estimated to be 6 MPa and $g = 2$ together with matrix stiffness $E_m = 40$ GPa and a fiber type similar to that of mix B of Table 1. These values fit the Compresit matrix very well. The value V_f^{max}, corresponding to maximum debonding energy, is calculated to $V_f^{max} = 30.9$ % resulting in $G_{deb} = 137$ N/m. The fracture energy of plain high-strength matrix is estimated to $G_{tip} = 100$ N/m, which corresponds well with the values measured on plain Compresit matrix. Using these fracture energies, it is obvious that the maximum $G_{deb} < 10G_{tip}$ and that no solution to (3) is possible. A method to increase the theoretical G_{deb} is to increase τ or L_f, because G_{deb} varies with τ squared and L_f cubed. However, this eventual modification tends to cause fiber breaking instead of pull-out which leads to brittle failure, see [1].

A reverse calculation is performed on the Compresit results where G_{tip} is 100 N/m as before, and $\sigma_{pc} \approx 6V_f(L_f/d_f)$ MPa from the experimental observations. We have that $G_{deb} = 5\sigma_{pc}w^*/6 \geq 10G_{tip} = 1$ kN/m from (3). Furthermore, it is assumed that this condition is only just fulfilled when the fiber reinforcement index is $V_f(L_f/d_f) \approx 1$, which gives $w^* \approx 0.2$ mm. By looking at Figure 2 and 3, it is assured that this value has the correct magnitude for the experimentally observed crack openings corresponding to the post-crack strength. Therefore, it seems that the theoretical behaviour of w^* in (2) is inadequate to model situations with high contents of steel fibers.

In [7], a so-called Cook-Gordon effect is included in the micromechanical model. This effect takes into account that a fiber is already debonded over a considerable length just before a crack tip reaches it. This is due to the stress field right in front of the crack tip. The pre-debonded length is termed the Cook-Gordon parameter. An elastic extension of the pre-debonded fiber should be added to the crack widths from the start. Thus, for each stress level given in (1), an extra deformation is added to w so that the crack widths are generally increased, see [7].

CONCLUSIONS

For various fiber contents and fiber geometries, the post-crack relationship is recorded for Compresit matrix. The test results are compared to a micro-mechanical model in order to predict the influence of the fiber parameters on the post-crack characteristics of FRC. The conclusions are:

1. The model prediction of the post-crack strength sustained by the fibers crossing a crack is proportional to the interfacial fiber-matrix bond strength and to the fiber reinforcement index defined by $V_f(L_f/d_f)$. An effective bond strength of approximately 6 MPa is plausible for Compresit.

2. The experiments indicate that, when the fiber reinforcement index exceeds 1, both steady-state cracking and multiple cracking seem possible. However, this is not in agreement with the theoretical micro-mechanical model. Therefore, a revision of the model is needed. It is noted that the conclusion is drawn from notched specimens.

3. For low contents of steel fibers or low-stiffness fibers, the micro-mechanical model is known to provide good results, cf. [7]. However, in order to predict the post-crack behaviour with high contents of steel fibers, some of the basic assumptions of the model may need further investigation. The reduced fiber spacing in the case of high amounts of steel fibers, probably gives rise to various fiber/matrix and fiber/fiber interactions that are significant. A possible interaction is the Cook-Gordon effect, but more research is needed to determine its significance.

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NOTATION

d_f, L_f, V_f	Fiber diameter, fiber length and fiber content.
E_m, E_f	Moduli of elasticity of matrix and fibers.

g	Snubbing factor defined in [6], $g \geq 1$.
G_{deb}	Fracture energy during fiber debonding.
G_F, G_{pull}	Fracture energy during fiber pull-out.
G_{tip}	Fracture energy of the plain matrix.
V_f^{crit}	Lower limit of fiber content for steady-state cracking.
V_f^{max}	Fiber content corresponding to maximum G_{deb}.
$V_f(L_f/d_f)$	Fiber reinforcement index.
w	Absolute crack width.
$\hat{w}$	Crack width normalized with respect to $L_f/2$.
w^*, $\hat{w}^*$	Crack widths corresponding to σ_{pc}, see (2).
η	Parameter dependent on fiber/matrix stiffness, see (2).
σ_B, σ_f	Total bridging stress and fiber bridging stress across a crack.
σ_{cr}, σ_{pc}	First cracking strength and post-crack strength.
σ_{fu}	Tensile strength of fibers.
τ, τ^*	Interfacial fiber-matrix bond strength and effective bond strength.

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