

PULLOUT BEHAVIOUR OF FIBERS IN STEEL FIBER REINFORCED CONCRETE

AUSZIEHVERHALTEN VON FASERN IN STAHLFASERBETON

COMPORTEMENT A L'ARRACHEMENT DE FIBRES D'UN BETON RENFORCE DE FIBRES D'ACIER

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SUMMARY

In extensive studies the pullout behaviour of steel fibers has been investigated. This is of major importance as it governs the behaviour of steel fiber reinforced concrete after matrix failure. The tests revealed the influence of fiber-matrix adhesion and clarified the contribution of the fiber geometry to the total stress absorbed by the fiber.

ZUSAMMENFASSUNG

In umfangreichen Arbeiten wurde das Ausziehverhalten von Stahlfasern untersucht. Dieses ist von großer Bedeutung, da es das Verhalten von Stahlfaserbeton nach dem Versagen der Betonmatrix bestimmt. Die Versuche zeigten den Einfluß der Faser-Matrix-Bindung und klärten den Anteil der Fasergeometrie an der Gesamtspannung, die von der Faser aufgenommen wird.

RESUME

De nombreux essais ont été effectués pour étudier le comportement de fibres d'acier à l'arrachement. Ce comportement est d'importance majeure, car il détermine le comportement du béton renforcé de fibres d'acier après la défaillance de la matrice. Les essais effectués ont révélé l'influence de l'adhésion fibre-matrice et mis en évidence la contribution de la géométrie de la fibre à la tension totale absorbée par celle-ci.

KEYWORDS: steel fibers, pullout, acoustic emission

1 INTRODUCTION

Apart from its excellent properties, concrete shows a rather low performance when subjected to tensile stress. Although in constructions pure tensile forces acting on concrete elements are rather scarce, this is not only an academic problem. Even a simple concrete bar under bending conditions has zones with high compressive as well as high tensile stresses.

The traditional solution to this problem is reinforced concrete, where reinforcing bars or prestressed steel bars inside the concrete elements are capable of absorbing the appearing tensile stresses. Another rather recent development is steel fiber reinforced concrete (sfrc). By adding steel fibers while mixing the concrete, a so-called homogeneous reinforcement is created. This does not notably increase the mechanical properties before failure, but governs the postfailure behaviour. Thus, plain concrete, which is a quasi-brittle material, is turned to the pseudoductile steel fiber reinforced concrete.

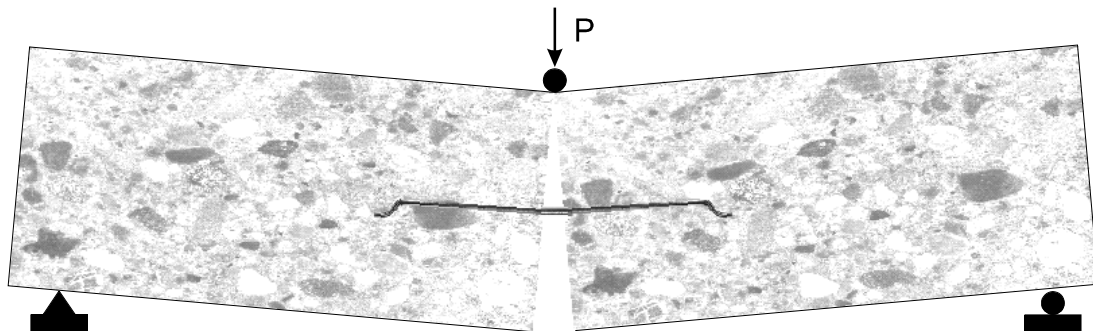


Fig. 1: *Principle of fiber reinforcement*

After matrix crack initiation, the stresses are absorbed by bridging fibers, and the bending moments are redistributed. The concrete element does not fail spontaneously when the matrix is cracked; the deformation energy is absorbed and the material becomes pseudo-ductile.

The present work is part of a project aiming at the characterization of the damage process in steel fibre reinforced concrete. Due to the random distribution of the fibers in sfrc, this is a rather difficult task. To set about solving this problem, we first of all focussed on the behaviour of a single fiber.

2 STEEL FIBERS

Research and design of steel fiber reinforced concrete began to increase in importance in the 1970s, and since those days various types of steel fibers have been developed. They differ in material as well as in size, shape and surface structure, as shown in figure 2. Due to different manufacturing processes and different materials, there are differences in the mechanical properties such as tensile strength, grade of mechanical anchorage and capability of stress distribution and absorption.

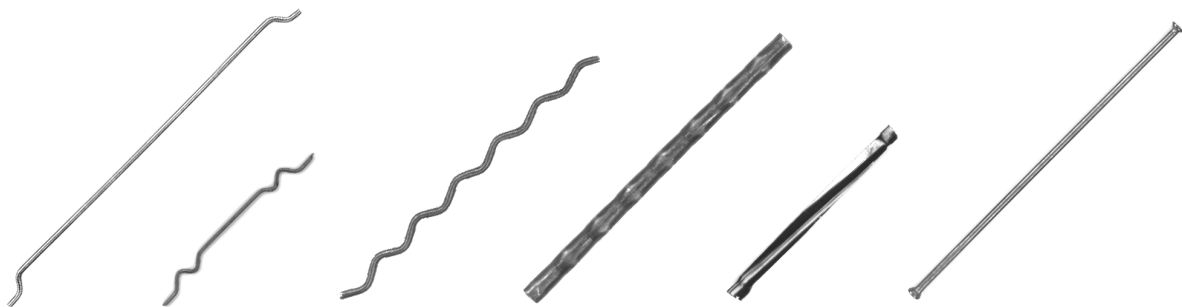


Fig. 2: *Different types of steel fibers*

There are drawn wire fibers, cut sheet metal fibers and milled steel fibers. Melt extracted fibers are amorphous and thus stainless. In order to improve anchorage and adhesion with the concrete matrix, the shape can be designed with hooked ends, completely corrugated or provided with end cones. Furthermore, for some types, the cross section of the wire is deformed. Milled fibers have a completely irregular shape. Most of the fibers are supplied as

single fibers, however, some are magnetically aligned and some glued together in bundles in order to ensure a better distribution after casting.

According to all these differences, also the effect of the fibers on the behaviour of concrete under load is fairly different. It ranges from crack control in case of fibers that are pulled out after the creation of macroscopic matrix cracks to an increase of the post peak load in case of fibers with an anchorage working up to steel tensile rupture. Still, there is only very little research work done on the behaviour of the fiber itself, the capabilities of the fibers are not yet completely understood, and still the design of steel fibers is influenced rather by experience than by scientific knowledge.

3 EXPERIMENTAL

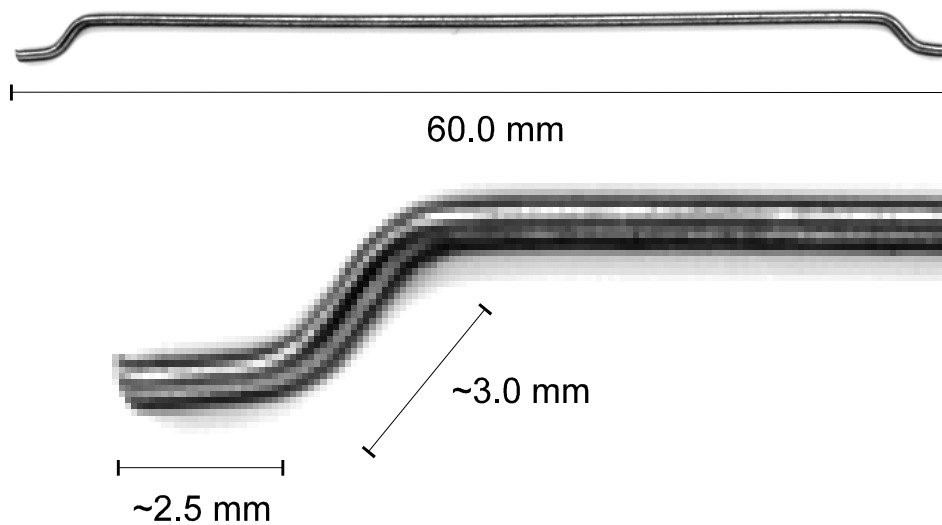


Fig. 3: *Dimensions of the DRAMIX® ZC 60/.80 fiber and its end part*

The fiber being studied was a cold drawn steel wire fiber of a Belgian manufacturer and is shown in figure 3. It had a diameter of 0.8 mm, a length of 60 mm, a tensile strength of 1000 N/mm^2 and hooked ends. This seemed very important for this study, as not fiber failure should be dealt with, but fiber pullout and effects due to the special fiber geometry.

The first series of tests were pullout tests with the matrix cracks and degradation being monitored using the acoustic emission technique. References to this technique can be found in [LANDIS AND SHAH, 1993] and [OHTSU ET AL, 1991]. Concrete cubes with an edge length of 15 cm and a single fiber embedded at half-length were taken for specimens as shown in figure 4. The free end of the embedded fiber was sealed in a perspex tube with a special glue in a way that it could be fixed between the clamping jaws of a 10 kN testing machine. During the test, this machine was running at constant rail speed. This type of test provided a good insight on the course of events in the material after macrocrack formation.

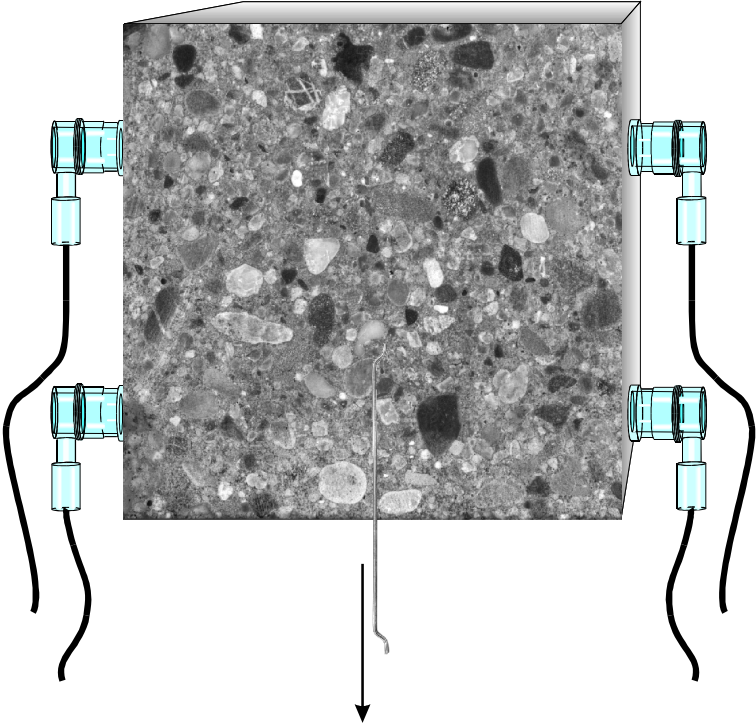


Fig. 4: *Test setup of first test series*

The second series were pullout tests as described above, but the hooked ends of the fibers had been cut off. It was intended to separate the effects of the fiber geometry from the effects of the fiber-matrix adhesion. This type of test seemed a way to study the latter.

Finally, tests on fibers that were dipped in liquid wax before embedding them in a tube of epoxy resin were carried out. This way, it was possible to eliminate the fiber-matrix adhesion and at the same time to observe directly the fiber during its pullout.

4 RESULTS AND DISCUSSION

4.1 Pullout curves

The first information provided directly during the tests were the pullout curves.

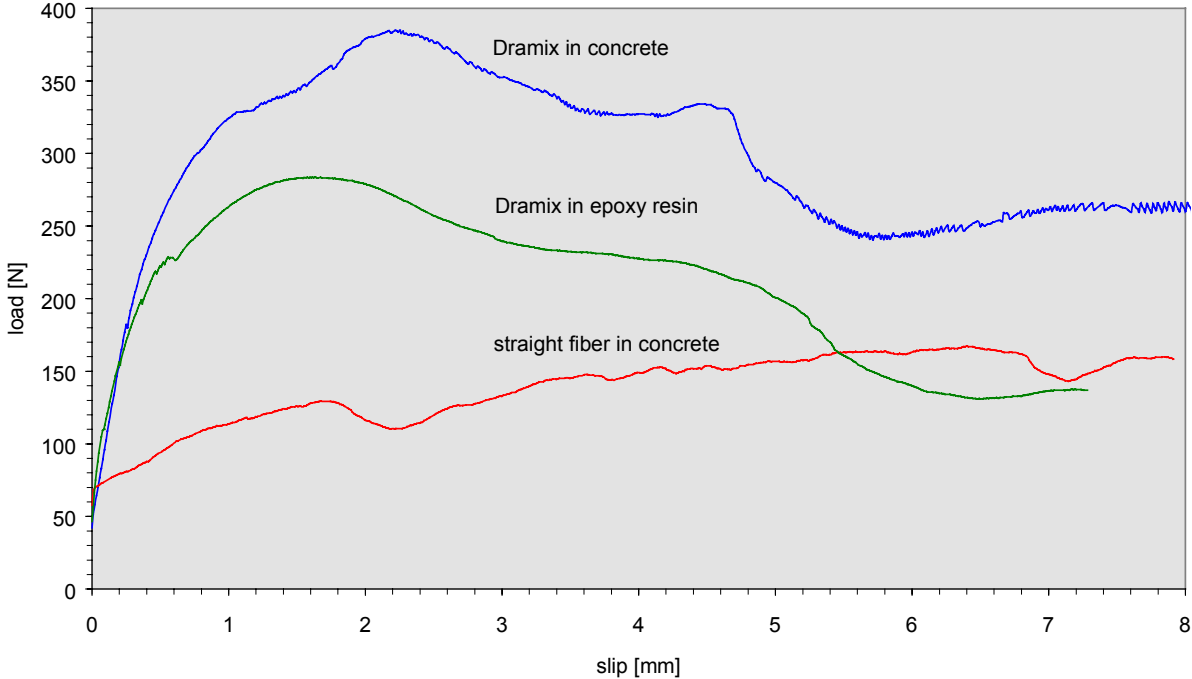


Fig. 5: *Load-slip curves of the Dramix fiber (top) and a straight fiber (bottom) in concrete, and a waxed Dramix fiber (middle) in epoxy*

Figure 5 shows representative pullout curves of all three test series merged into one plot. As expected, the fiber-matrix-adhesion as well as the geometry of the fiber give contributions to the pullout behaviour of the fiber. Adding the two lower curves of figure 5, one gets an approximation of the higher pullout curve. This fact already has been stated before [BOYAZIS, 1979],

however, it was not recognized that only the first 6 mm of the pullout are typical of this type of fiber. Moreover, in structures, the stress redistribution due to the fibers avoids crack opening distances beyond this value. That is why only the first few millimeters of the pullout are of importance.

To start with the hooked fibers in concrete, the following behaviour of the load can be observed: increase up to a maximum - slight decrease followed by a second maximum - extreme descent leading to a zigzag behaviour. This characteristic division into three stages also appears in the pullout curves of the hooked fiber from epoxy resin, however smoother and free of fluctuations. In contrast, during the whole way out from the concrete, the load acting on a straight fiber is slightly increasing, with small accidental changes.

The interaction of the fiber and the concrete matrix results in an almost constant load with small fluctuations due to the changing concrete environment of the fiber on its way through the channel. This load is superimposed by the effects of the fiber geometry, which are more difficult to explain. In all tests carried out on hooked fibers pulled out from epoxy resin, two maxima and an almost constant load after 6 mm of pullout were observed. This is a strong evidence of the influence of the fiber tip's two angles, ending when the fiber is straightened.

4.2 Acoustic emission on hooked fiber pullout tests

The results of the acoustic emission analysis have been presented and discussed in detail in another paper [WEILER, GROSSE, and REINHARDT, 1996]. Figure 6 shows, for a typical test, two plane projections of acoustic emission localizations. All events are located in an area in the middle of the cube, at a height of 2 to 3 cm. Event locations of the early pullout stage are represented by a filled circle, later events by an open square, and the last stage by a triangle. Although the locations are spreading, the different stages as described in the previous chapter can be separated: The average z value of all event locations in

the first two stages are about 2.85 cm and 2.28 cm, respectively. Also in the waveforms, distinct differences can be found: The last stage, assumed to be governed by friction, exhibits a single dominating frequency, whereas the early stages, governed by microcracks, have a wide spectrum of different frequencies.

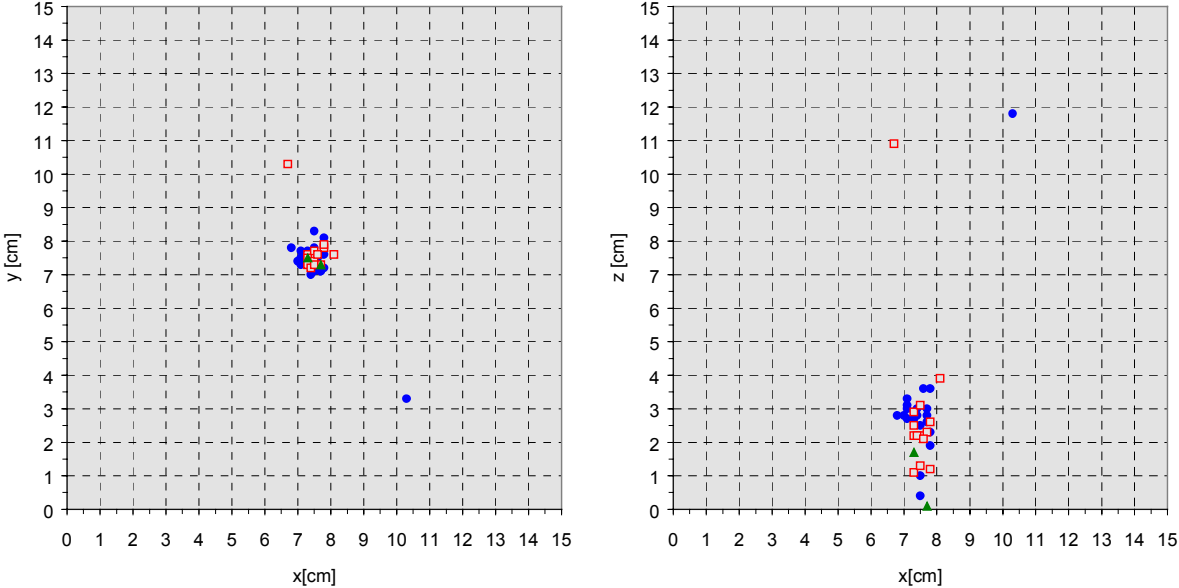


Fig. 6: *xy-projection (left) and xz-projection (right) of AE locations of different pullout stages*

These tests confirm the statements made in the previous chapter concerning the influence of the fibers ends. Moreover, they justify the translation of the results from the model material epoxy resin to the real material concrete, although, of course, the crack mechanisms and the elastic properties of these material are completely different.

4.3 Direct observation of the fiber pullout

The previous results do not provide a complete understanding of the fiber behaviour during the pullout. To achieve this in situ, extensive x-ray tests on modified concrete specimens would be necessary. Another solution is the direct observation of the process through the transparent matrix of epoxy resin. Four snapshots of a video recorded during one of these tests are shown in figure 7.

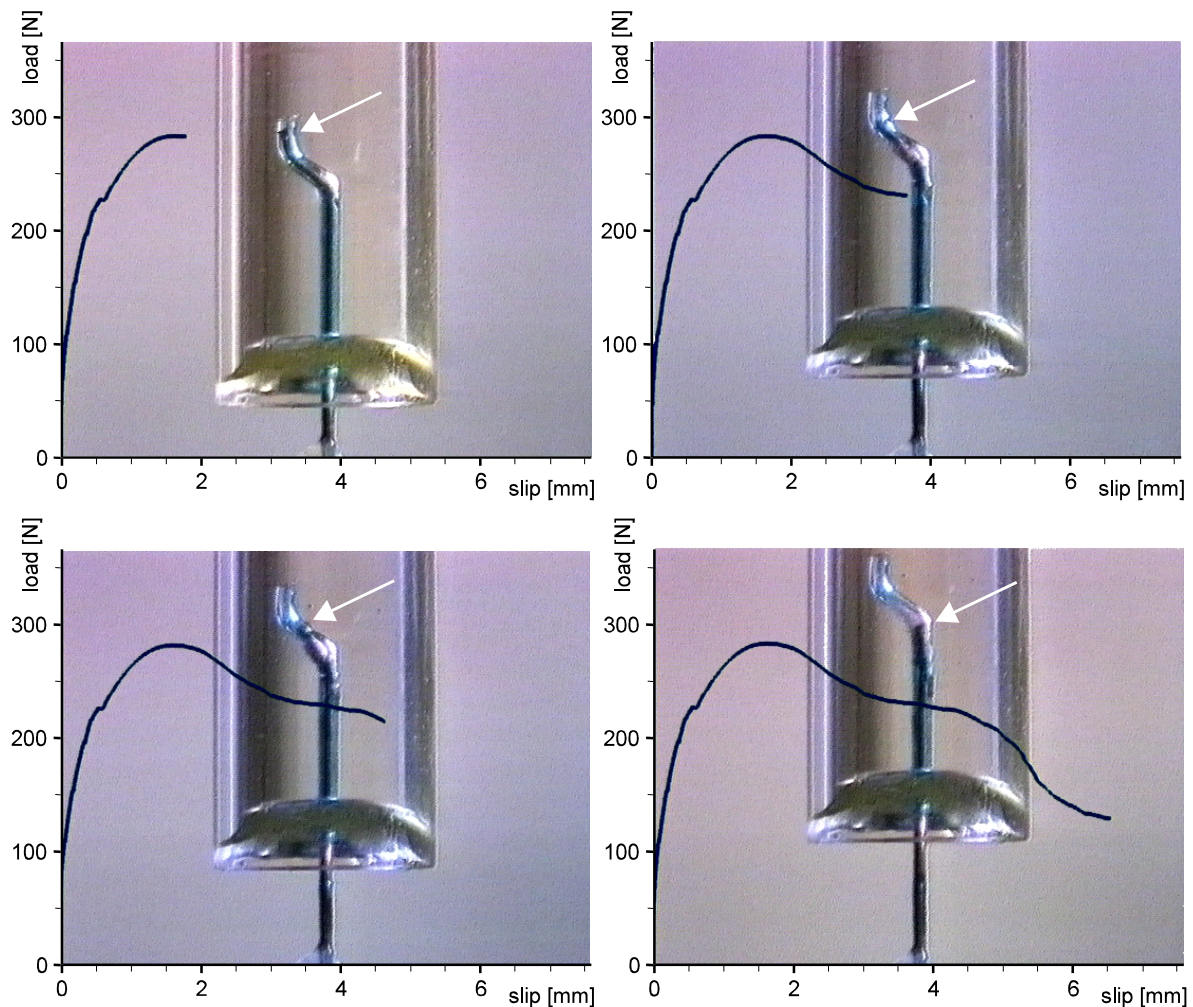


Fig. 7: *Model tests: Pullout curve of pullout test in epoxy resin combined with photos of different stages of the test*

These pictures enable a direct correlation of the applied load with the fiber's shape and its position in the channel at different stages of the pullout. The load is the sum of different components. The initial steep slope is caused by elastic deformation of the straight part of the fiber and its debonding from the matrix. As the fiber begins to be pulled out, continuous plastic deformation of the fiber end, and, as a cause of the acoustic emissions, deformation of the surrounding matrix becomes predominant. Thus, the first load maximum has its reason in a partial straightening of the upper fiber angle which is made possible

by deformations around the two edges of the channel when the fiber tip is forced in the upper angle at a slip of 2 mm. In the case of epoxy resin, the deformations of the matrix are elastic, decreasing after the total straightening of the fiber as can be seen in the last picture of the series. In contrast, concrete is deformed inelastically by means of microcrack formation, the energy being released by acoustic emissions in the angled area. This way, also the second maximum can be explained. It is the final fiber straightening, again accompanied by an extreme deformation of the matrix at the lower angle of the channel. The load is lower than in the previous case, as only one angle is subject to deformation.

5 CONCLUSIONS

Different tests have been carried out in order to gain a better understanding of the pullout behaviour of steel fibers. For this purpose, a commonly used fiber was chosen. Tests with waxed fibers revealed the effect of the fiber geometry, which is of major importance for this type of fiber with hooked ends. The correlation of these results with results of acoustic emission tests on concrete specimens clarified the interaction of the matrix and the fiber at the hooked end. This interaction is capable of carrying most of the applied load while the fiber itself gets straightened and the surrounding matrix is being degraded. As was shown during pullout tests of straight fibers, the concrete matrix only absorbs a small part of the load by friction. Many random parameters of the matrix have effects on this constant, but varying load: aggregate distribution, presence of air bubbles, reduced adherence between steel and concrete matrix, cavities, and so on.

This work gives a first and satisfying insight in the basics of fiber reinforcement. However, many aspects have not yet been considered. First of all, the fibers are usually inclined with respect to the cracked matrix plane. Thus, the effect of different pullout angle should be also investigated.

Approaching more and more the real material, the interaction of fibers that are statistically dispersed, and their interaction via aggregate grains should be taken into account as well. Parameters that can be varied in wide ranges in this concern are the grain size distribution and the fiber dimensions. Length and orientation of the fiber interact with the grains and considerably affect the mechanical behaviour. Finally, the reaction of the material to different load configurations is another important aspect.

6 ACKNOWLEDGEMENTS

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