ANALYSIS OF SYNTHETIC FIBER PULL-OUT FROM A CEMENT MATRIX

Youjiang Wang*, Victor C. Li**, and Stanley Backer*
* Department of Mechanical Engineering;
** Department of Civil Engineering,
Massachusetts Institute of Technology, Cambridge, MA 02139

ABSTRACT

Experiments were conducted on specimens containing nylon or polypropylene monofilaments embedded in a precracked matrix. During pull-out tests, it was generally observed that the pulling force continued to increase after one or both sides of the filament had begun to slip out, even though one or both of the embedded filament lengths were decreasing. This indicated that the fiber/matrix shear stress increased with the fiber slippage distance. Examination of the extracted filaments under a scanning electron microscope (SEM) revealed the increased shear resistance to be the result of fiber surface abrasion. The severity of abrasion was observed to increase with the fiber slippage distance before complete pull-out. A theoretical model has been developed to predict the pull-out force versus displacement relationship based on given fiber/matrix shear strength as an increasing function of the slippage distance. The model gives good prediction in comparison with experimental results.

INTRODUCTION

Fiber/matrix bond allows stress transfer between individual fibers and the matrix. Because of its important role in composite materials, the fiber/matrix interface has been studied extensively. Many researchers have investigated the effect of the interfacial bond on composite properties, the stress state at the interface, and experimental measurement of the fiber/matrix bond strength. Their work has been reviewed by Chamis [1] for fiber reinforced polymeric composites and by Bartos [2] for fiber reinforced concrete (FRC).

Fibers often used in FRC are steel fiber, glass fiber, and various synthetic fibers (e.g. aramid, nylon, polypropylene). Most of the work on the fiber/matrix bond in FRC has been on steel and glass fibers, and the results have been summarized in [2]. Less information on the bond for synthetic fibers is available, although some work has been done on this subject [3,4,5,6]. Frequently, the fiber/matrix bond strength is obtained from fiber pull-out tests and is given by an average value over the fiber surface area. Such bond strength, of course, does not represent the real stress state at the fiber surface. Solutions to the fiber pull-out problem based on an elastic bond strength and a constant and uniform post-elastic frictional bond strength have been obtained [7,8].

In all the theoretical models reported for FRC, the fiber/matrix bond is generally characterized by: (1) a uniform bond shear strength; or (2) elastic and frictional bond strength parameters, which have unique values for an FRC. This, however, is not necessarily the case for all fibers, particularly synthetics. Due to their highly oriented structures, synthetic fibers are easily abraded by cement particles during pull-out. As the fiber surface abrasion becomes more and more severe, the apparent fiber/matrix bond strength increases. This has been observed in this study on nylon and polypropylene fibers, and noted previously by Baggott and Gandhi [6] in polypropylene FRC.

This paper first presents the results of fiber pull-out tests on nylon and polypropylene fibers. A theoretical model to describe the pull-out test based on the experimental observation is briefly described. Finally, these results and their implications on FRC behavior are summarized. The primary objective of this study is to understand the behavior of a fiber in an FRC member during fracture, and, with additional considerations of fiber orientation and fiber distribution, to predict the constitutive relations of FRC.

EXPERIMENTS

Specimen Preparation and Testing

The test specimens consist of monofilaments embedded across a precrack in the cement matrix. The fiber segments inside the two sides of the matrix, which is separated by the precrack, have different lengths: 50 mm and 70 mm. The geometry of the specimens is illustrated in Figure 1. The fibers used in the specimens were nylon and polypropylene monofilaments, both of 0.508 mm in diameter, manufactured by the DuPont Company and the Albany International Research Company respectively. Type III high early strength cement was used to form the matrix.

Plexiglas boxes were used as the molds for the specimens. The precrack in the matrix was obtained by placing a thin PVC plastic sheet (0.8 mm in thickness) in the mold before casting. The plastic sheet had a hole of 8 mm in diameter in the center to permit fiber passage. Cement slurry was prepared by thoroughly mixing cement and water by hand. To achieve good fluidity, a high water/cement ratio of 0.6 by weight was used. Before being put into the matrix, the fibers were first straightened by heat-relaxing of the on-package curvature, by immersing the fiber in hot water for one minute under a tension of 10 N and then cooling and air drying for a few hours. The temperature was 75° C for relaxing the nylon fibers and 95° C for polypropylene. The fiber was razor cut into required lengths, then held in tweezers to ensure proper alignment during casting.

After casting, the specimens were plastic wrapped and cured at 25° C. Before testing, the plastic molds were carefully removed from the specimens. The specimen age at testing was three days. The pull-out tests were performed on a universal Instron machine, with the specimen held by a pair of friction jaws. Crosshead speed was 12.7 mm/min. Pulling force vs. crosshead displacement was recorded for each specimen. For the load range of these tests, deformations of the testing machine and the cement matrix were negligible, therefore crosshead displacement can be regarded as the specimen crack separation. Four specimens with nylon fibers and four with polypropylene were tested. These test results are shown in Figure 2.

Discussion of Test Results

The load vs. crack separation curves for the pull-out test shown in Figure 2 manifest some very interesting features. First, after the fiber is completely debonded from the matrix, the pull-out force does not drop, or may even increase, during most of the period of fiber pull-out. Second,the final crack separation distance is greater than the length of the shorter fiber segments embedded in

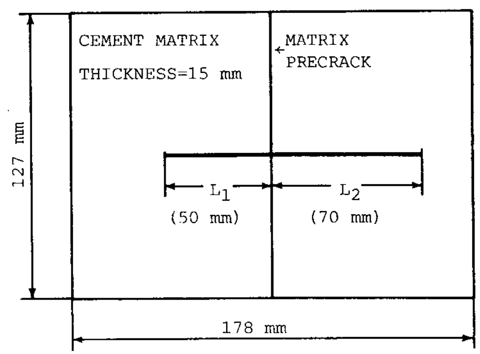

Figure 1. Illustration of Specimen for the Pull-Out Test

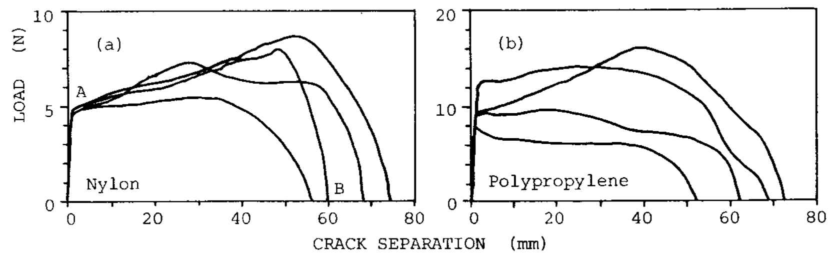

Figure 2. Load vs. Crack Separation Curves for the Pull-Out Tests

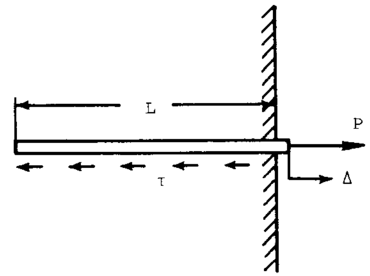

Figure 3. Determination of Load-Displacement Relation at Complete Debonding

one side of the matrix, indicating that fiber slippage occurs in both the shorter and the longer segments. This of course assumes that the fiber remained elastic since the load imposed was only a few percent of the filament strength.

Consider a typical test curve for the nylon fiber pull-out tests labeled as OAB in Figure 2a. In this curve, Part OA represents fiber partial debonding during which the length of fiber elastically bonded to the matrix decreases. Point A at which the slope of the curve decreases abruptly corresponds to the completion of fiber debonding (for the shorter segment), when the fiber end begins to slip. And Part AB is for fiber slip-out resisted by friction. The point corresponding to fiber complete debonding of the elastic bond can be determined by considering a simple model illustrated in Figure 3. The fiber shown corresponds to the shorter segment of fiber in one side of the matrix, with a length of L, diameter d, and tensile modulus E_f. At complete debonding, by definition, the entire fiber segment has debonded and the shear stress field is dominated by friction. Assuming a constant frictional bond strength, we can obtain the load P and fiber elongation Δ in terms of the bond strength τ [9]:

$$P = \pi d L \tau \quad (1)$$

$$\Delta = 2 \tau L^2 / (E_f d) \quad (2)$$

Combining Eq (1) with Eq (2), and noticing that the total crack separation δ consists of elongations of fiber segments in both sides of the matrix, we may relate the load with crack separation at complete debonding:

$$\delta = 4 L P / (\pi d^2 E_f) \quad (3)$$

Putting d = 0.508 mm, L = 50 mm, E_f = 1 GPa, and P = 4.5 N (from Figure 2) into Eq(3), we get an estimate of δ = 1.23 mm, which confirms that the bend-over points in the test curves (Point A in Figure 2a) indeed correspond to complete fiber debonding. The above assumption of a constant frictional bond strength (τ) is justified in light of the small amount of fiber sliding inccured prior to complete fiber debonding.

After complete debonding, the fiber starts to slip out and the pull-out force is balanced by the friction between fiber and matrix. The frictional bond strength (τ) may change with fiber slippage distance (s) with respect to the matrix, depending on the properties of fiber and matrix. Figure 4 shows schematically the dependency of the pull-out test results on the τ-s relations. For constant bond strength ($d\tau/ds=0$), the load after complete debonding drops almost linearly as the crack separation increases, and the pull-out occurs only in the shorter fiber segment. (The slight nonlinearity is due to fiber stress relaxation). The curve for $d\tau/ds<0$ is typical for steel fiber pull-out tests [e.g. 10]. The deviation from a simple linear fall off in pull-out can be attributed to the stiffness and hardness of the steel fiber which causes a breakdown of the cement at the fiber/matrix contact points during fiber withdrawal. The pull-out test curves for nylon and polypropylene fibers fall into the category represented by the curve for $d\tau/ds>0$ in Figure 4. In this case, after complete debonding the load may go up or down, depending on the particular bond characteristics (the τ-s relation) and the fiber embedded lengths. In any event, the load at a given crack separation as seen in Figure 2 is always higher than that for constant bond strength ($d\tau/ds=0$). In addition, slippage of the longer fiber segment is possible.

The mechanisms involved in synthetic fiber pull-out from a cement matrix are different from those for steel fiber pull-out. Synthetic fibers are highly oriented structures composed of long-chain molecules which essentially lie in the direction of the fiber axis. These fibers usually have very low transverse compressive and shear strength and are susceptible to surface scratch. When the fiber is being pulled out from a cement matrix, the contact points of the matrix may act as indentors abrading to the fiber surface. Due to the fiber microstructure, the wear debris may not be separated from the fiber, and as a result further pull-out will cause peeling and fibrillation at the fiber surface. Such actions make the fiber bulkier, thus increasing lateral pressure and with it the frictional shear resistance to further fiber slippage. This abrasion effect, of course, is dependent on the fiber type and the processing conditions.

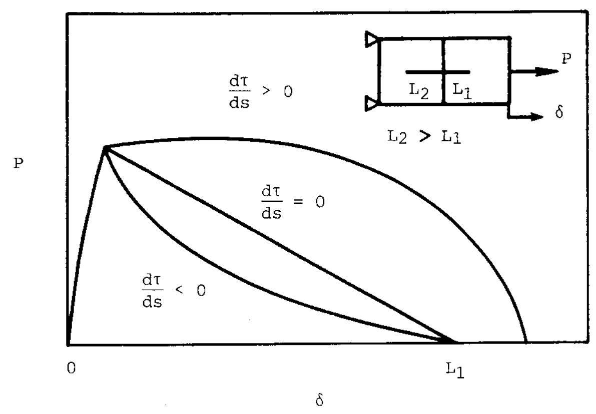

Figure 4. Schematic Illustration of the Effect of τ–s Relationship on Pull-Out Result

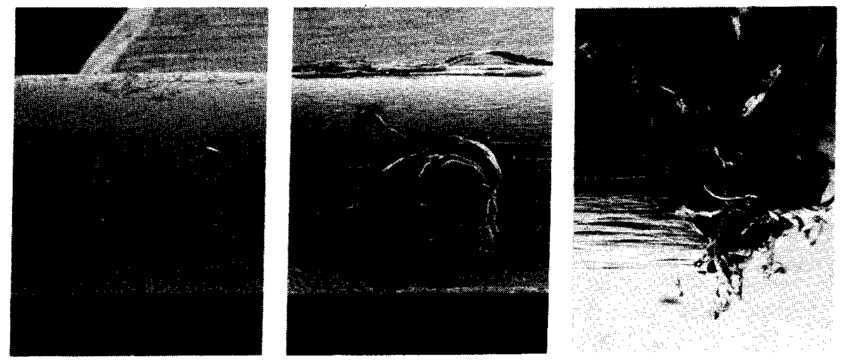

Figure 5. SEM Graphs of the Surface of a Nylon Fiber Pulled Out from the Matrix (s=slippage distance)

Figure 5 shows the SEM pictures of the surface of a nylon fiber pulled out from a matrix. These pictures were taken from different fiber segments which underwent different slippage distances before emerging from the matrix. The pictures clearly show peeling and fibrillation at the fiber surface. It is also worth noting that the severity of fiber surface abrasion increases more rapidly at long slippage distances than at the beginning of slippage, which may reflect the cumulative effect of abrasion. It was noted in Figure 2 that the loads at a given pull-out displacement after complete fiber debonding and the final crack separation varied considerably from specimen to specimen. This indicated the stochastic nature of the pull-out process due to variations in the local properties of the fiber and the matrix at their interface.

In summary, fiber bridging is known to be one of the main toughening mechanisms in the fracture process of synthetic fiber reinforced concrete. Fiber slippage with respect to the matrix is involved during fiber pull-out with possible exception only at the start. Fiber slippage can change the fiber/matrix bond characteristics drastically, particularly for synthetic fibers. It is inaccurate to simply use a constant frictional bond strength to describe the fiber pull-out process after complete debonding of the elastic bond. A theoretical model is needed which should reflect the variation of the frictional bond strength during pull-out, and give a close prediction of the pull-out test.

THEORETICAL ANALYSIS

We have developed a theoretical model to predict the load-crack separation relationship for synthetic FRC. The bare outline of the model is provided here. Due to space limitations, details are furnished in a forth-coming paper.

The distinctive feature of the model lies in the recognition that the fiber/matrix bond strength (τ) at any point on the fiber is a function of the slippage accumulation at that fiber segment. In light of the suggestion by Baggott et al [6] that slight fiber misalignment and the presence of channel-surface asperities could offset the Poisson effect, considered in [6, 11, 12], we have omitted the Poisson effect from this initial model. Also omitted is the contribution of the elastic bond strength to the overall pull-out load-displacemnet curve. On the basis of Gopalaratnam and Shah's model

[8] we have determined that the elastic bond strength has little effect for low modulus fibers and therefore frictional bond strength dominates the pull out resistance. The modelled fiber is accordingly assumed to be linear elastic with sufficient strength to enable complete pull-out without rupture. The contribtution of matrix deformation to crack separation is neglected as well.

In a single (one-sided) direct fiber pull-out test it is accepted that the slippage accumulation of a given fiber segment at (X) must equal the sum of the slippage of the embedded fiber end at (O) and the elastic elongation of the entire fiber lying between (O) and (X). The local elastic strain at (X) is dependent on the fiber tension which in turn is determined by integration of the shear forces $\tau(X)$ from (O) to (X). The essence of the model lies in the polynomial dependence of local shear force on local slippage accumulation as determined in separate experiments. Four coupled nonlinear equations are formulated from this physical model and solved numerically at each loading stage to determine corresponding free end displacements.

In the double (two-sided) pull-out model, provision is made for simultaneous pull-out of a long and a short fiber section on either side of the matrix crack. The physics of the model requires that the force on the free (within matix crack) fiber section is constant and the net crack opening equals the sum of fiber slippage and elastic extension in both fiber segments. The shorter fiber segment is of course expected to slip first according to the force versus displacement model for single direct fiber pull-out, reaching a maximum when the interaction between residual embedded length and the frictional shear stress (enhanced by the prior slip accumulation) is reached. Up to this stage the ever increasing load also operates on the long fiber segment to cause debonding, frictional shear stressing, elastic elongation and free end displacement. It is in the region of decreasing force beyond the occurence of force maximum that the two fiber segments differ in their response, with the shorter segment continuing to withdraw at lower loads and the longer segment tending to shrink back into its matrix with cessation of its withdrawal. To determine the complete force displacement curve the small fiber segment withdrawal behavior is calculated. The loading, then unloading components of the force versus displacement curve of the longer segment are now determinced. The displacements are then added and the pull-out forces equated for different crack opening increments.

In comparing the calculated load versus crack separation relationship (Figure 6) based on the model outlined above with results of pull-out experiments (Figure 2), one notes that the model is indeed able to closely predict the pull-out test results, provided the τ-s relationship is properly determined. It is not however, a material characteristic and an alternative relationship based on the theory of friction and wear of fibrous polymer would be desirable.

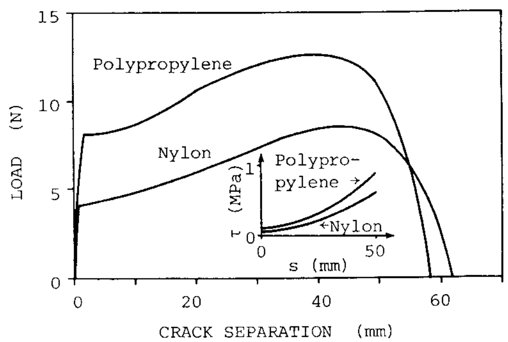

Figure 6. Theoretical Predictions for the Pull-Out Tests
(insert figure shows the τ-s relation used)

CONCLUSIONS

In experiments of nylon and polypropylene fiber pull-out from a cement matrix, fiber surface abrasion was observed. This increased the fiber/matrix bond strength during pull-out, resulting in higher pull-out force and energy absorption compared to the case of constant frictional bond strength. This effect no doubt contributes to the high energy absorption capability of synthetic FRC. The theoretical model developed for the pull-out test accounts for the bond strength variation during pull-out. Good prediction of the experimental load versus crack separation relationship is obtained.

ACKNOWLEDMENTS

The authors would like to acknowledge the support of the Shimizu Construction Company, Ltd. and the Program of System Engineering for Large Structures at the National Science Foundation.

REFERENCES

1. C.C. Chamis, NASA Technical Note: NASA TN D-6588 (1972).
2. P. Bartos, Int. J. Cem. Comp., 3 (3), 159 (1981).
3. S. Mindess and J. F. Yound, Concrete (Prantice-Hall, Englewood Cliffs, N.J. 1981).
4. Y. Wang, S. Backer and V.C. Li, J. Mat. Sci., in press (1987).
5. P.L. Walton and A.J. Majumdar, Composites, 6 (5), 209 (1975).
6. R. Baggott and D. Gandhi, J. Mat. Sci. 16, 65 (1981).
7. P. Lawrence, J. Mat. Sci. 7, 1 (1972).
8. V.S. Gopalaratnam and S.P. Shah, ASCE J. Eng. Mech., 113 (5), 635 (1987).
9. Y. Wang, SM Thesis, Dept. Mech. Eng. MIT, Cambridge, MA (1985).
10. A.E. Naaman and S.P. Shah, ASCE J. Structural Div., 102 (ST8), 1537 (1976).
11. A. Kelly and C. Zweben, J. Mat. Sci., 11, 582 (1976).
12. D.J. Pinchin, J. Mat. Sci., 11, 1578 (1976).