Effect of inclining angle, bundling and surface treatment on synthetic fibre pull-out from a cement matrix

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In an experimental investigation of synthetic fibre pull-out at an angle, it was generally observed that the force and energy of fibre pull-out increase with the inclination angle, but such increases are limited by the strength of the cement matrix at high angles due to matrix spalling. Studies were also conducted on the effects of fibre bundling and surface treatment on the pull-out behaviour. It is suggested that for effective use of the reinforcing fibres, fibre bundling should be minimized and the fibre/matrix bond property should be controlled.

Key words: *concrete; synthetic fibre pull-out; inclination angle; fibre bundling; surface treatment*

Fibre reinforcement is an effective and economical way to convert brittle concrete into a pseudo-ductile material. In the fracture process of fibre reinforced cementitious composites (FRC), fibre pull-out is the major mechanism contributing to the high toughness of the material. In this paper, the effect of fibre inclining angle, fibre bundling, and fibre surface treatment on synthetic fibre pull-out is studied by individual experiments as well as by theoretical analysis. The results illuminate methods of materials engineering in FRC, especially FRC with synthetic fibres.

In FRC containing randomly distributed fibres, few fibres align in the direction of the applied load, instead, almost all fibres are lying at angles to the load direction. When a fibre is pulled out from the cementitious matrix, the snubbing friction at the fibre exit point can increase the pull-out resistance, and contributes to the overall composite toughness.

Another phenomenon often observed in synthetic FRC is the tendency for fibres to form bundles in the matrix, particularly for certain types of synthetic fibres. The formation of fibre bundles reduces the number of fibres directly interacting with the matrix. It could also introduce weak spots along certain fibre bundles as the fibre bundles usually have low resistance to splitting. Consequently, lower crack resistance of the composite is resulted from the fibre bundles. For effective fibre reinforcement, the fibres should therefore be uniformly distributed in the composite matrix.

The behaviour of fibre pull-out is affected by the properties of the fibre/matrix interface. To derive the maximum energy absorption from the fibres bridging a matrix crack, the fibre/matrix bond should be controlled to achieve the highest pull-out resistance without rupturing the fibre. Possible ways of modifying the fibre/matrix bond characteristics through fibre surface treatment are studied and discussed.

ANGLE EFFECT ON PULL-OUT FORCE AND ENERGY

Before matrix cracking occurs under a uniaxial load in FRC, the axial strain in a fibre at an angle to the applied load is less than that of the composite, and thus its contribution to composite stress is less than that provided by a fibre aligned in the load direction. After matrix cracking, the load and energy required to pull a fibre out from the matrix can be higher for fibres lying at angles to the load direction, as observed in experiments with steel fibres.[1] The increase in load is due to the additional frictional snubbing force and the bending of the fibre at the corner of exit from the matrix.

The bending effect has been studied by Morton and Groves[2] in several metal fibre reinforced composites. Based on beam bending mechanics, their theory predicts that the maximum force due to bending occurs at an inclining angle equal to 45°, which is consistent with the results for steel fibres.[1] It can be shown, however, from their theory that the additional force due to fibre bending is often negligible for synthetic fibres as a result of their low bending stiffness. This is because the diameters of 'high modulus' fibres ($E_f \geqslant 70$ GPa) hardly ever exceed 50 μm, and often only low modulus fibres ($E_f \approx 10$ GPa) are available with larger sizes.

In this study, a set of experiments with nylon and polypropylene fibres were conducted to evaluate the angle effect on fibre pull-out behaviour.

Specimen preparation and testing

Nylon and polypropylene monofilaments used in this study were both 0.508 mm in diameter, manufactured by the DuPont Company and the Albany International Research Company respectively. The fibres were first straightened to remove the on-package curvature by immersing the fibre in hot water for one minute under a tension of 10 N and then cooled in the air and dried for a few hours. The temperature was 75°C for relaxing the nylon fibres and 95°C for polypropylene. 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. The specimen, shown in Fig. 1a, was cast by first attaching the fibre to a holder such that a fibre length of 25 mm was extruded into the plexiglas mold at a prescribed angle, ϕ, then pouring the cement slurry into the mold and levelling the free surface. The specimen was covered with plastic wrapping films after casting and cured for three days before testing. The tests were performed on a universal Instron machine (Fig 1b), at a crosshead speed of 12.7 mm min^{-1}. A plot of force *vs* displacement was recorded for each test, from which the maximum force and the total energy of pull-out were obtained. The fibre inclining angles tested were ϕ = 0°, 15°, 30°, 45°, 60° and 75°. Eight specimens containing nylon fibres were tested for each ϕ. Four specimens containing polypropylene fibres were tested for each ϕ in the range of 0°–45° and eight specimens for each ϕ of 60° and 75°.

A preliminary experiment has also been conducted on fibre pull-out from a high strength hardened cement paste (HCP), using the same nylon monofilament. The matrix was composed of Type III cement (1 kg), water (0.26 kg), condensed microsilica fume (0.133 kg) and superplasticizer (20 ml). Similar composition has been found to give a 7 day compressive strength over 80 MPa.[3] Only ϕ = 0° and 60° were tested, and the test for each angle consisted of eight specimens. Specimen age at testing was 14 days.

Results and discussion

In the following discussion, normal strength HCP is assumed to be the specimen matrix, unless it is explicitly stated that a high strength HCP matrix was used.

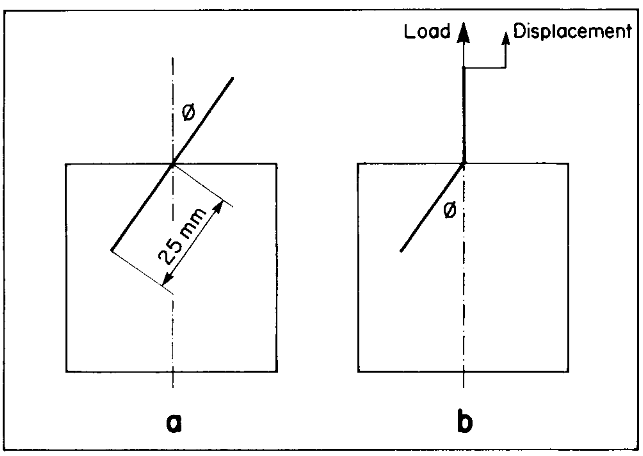

Fig. 1 (a) Specimen and (b) test schematic for experiments of fibre pull-out at an angle

The maximum load, P_{max}, *vs* the inclining angle, ϕ, is plotted in Fig. 2, and the pull-out energy, calculated from the total area under the load-displacement curve, *vs* ϕ is presented in Fig. 3. It can be seen from Fig. 2 that P_{max} increases with ϕ consistently over the range of ϕ = 0°–45°. At higher inclining angles (ϕ = 60° and 75°), the test data show significant scattering, and there are cases in which P_{max} decreases with ϕ. A similar trend can also be seen in the pull-out energy *vs* ϕ relationship from Fig. 3.

As illustrated in Fig. 4, when a fibre is pulled out from a matrix at an angle ϕ, the matrix wedge at the fibre exit point exerts a normal force, N, on the fibre to allow the axial force in the fibre to change its direction. A frictional force, F, contributing to the load increase is caused by this normal force and the relative movement between the fibre and the matrix. At high inclining angles, the required normal force is higher but the matrix wedge is sharper and therefore weaker. As a result, the matrix wedges will spall off causing sudden load drops in the test curve typified by that shown in Fig. 5. After each completion of wedge spalling off, a new more stable wedge is formed, and the fibre segment remaining in the matrix will then be pulled out. The actual length of pull-out can be measured from the load-displacement curve, as indicated in Fig. 5, and it is plotted against the inclining angle ϕ in Fig. 6. The pull-out length provides information on the size of the wedge spalled off, indicated by the difference between the original embedded length and the pull-out length. The matrix spalling is more severe at high inclining

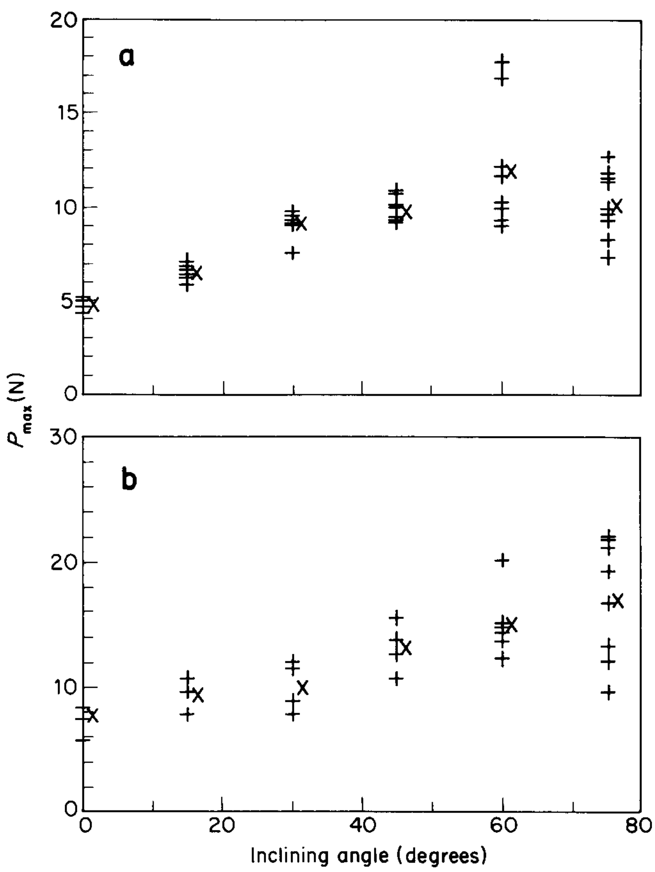

Fig. 2 Maximum load (P_{max}) *vs* inclining angle (ϕ): (a) nylon; (b) polypropylene. '+' indicates individual test data and '×' indicates the group average

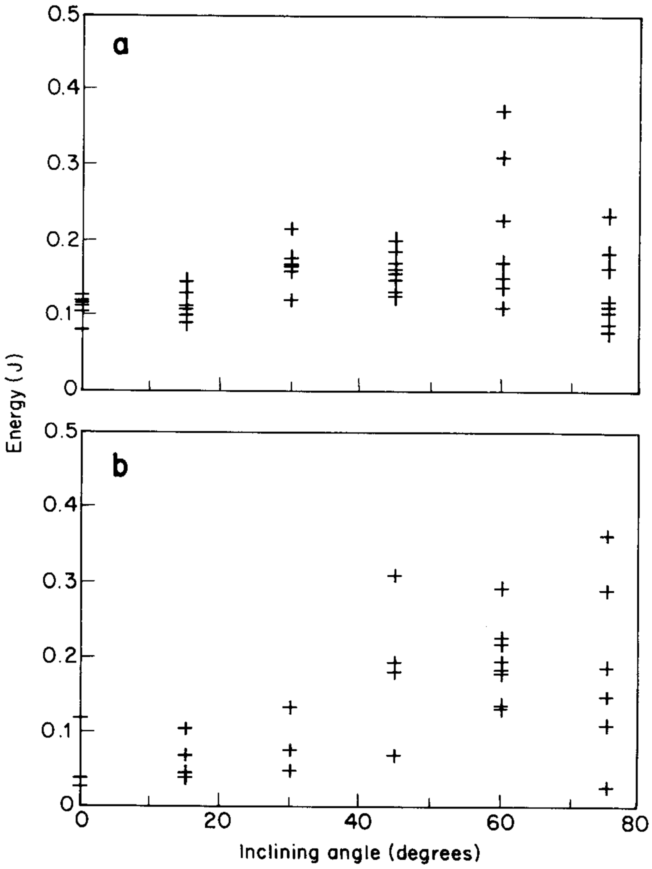

Fig. 3 Pull-out energy *vs* inclining angle (ϕ): (a) nylon; (b) polypropylene. '+' indicates individual test data and '×' indicates the group average

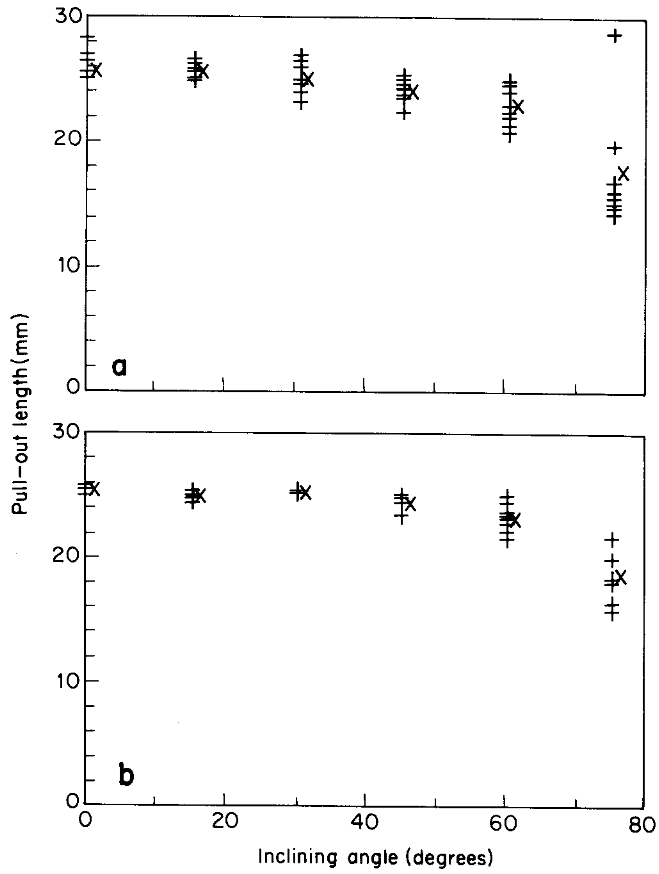

Fig. 6 Pull-out length *vs* inclining angle (ϕ): (a) nylon; (b) polypropylene. '+' indicates individual test data and '×' indicates the group average

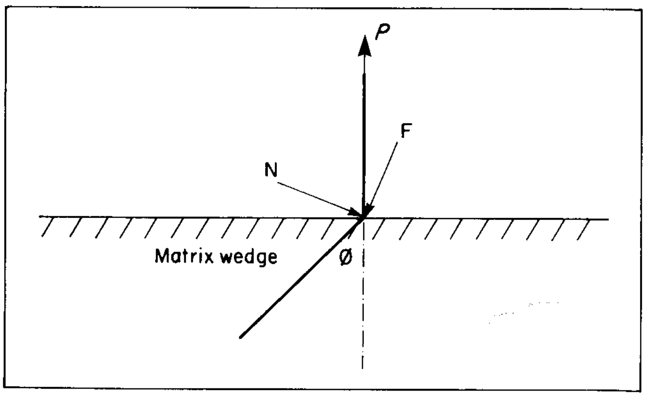

Fig. 4 Illustration of fibre pull-out at an angle

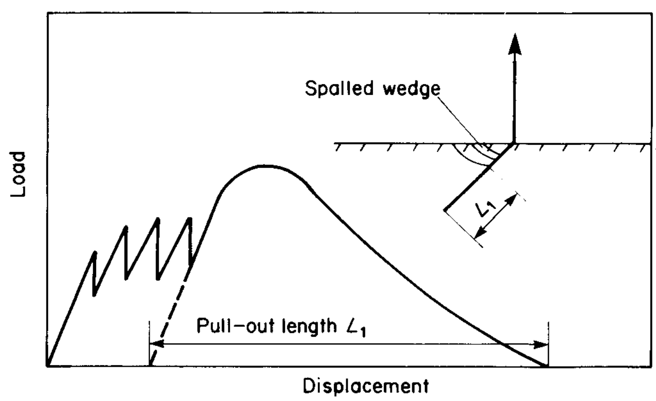

Fig. 5 Typical load-displacement curve for the pull-out test

angles, as seen from Fig. 6 which shows that the pull-out length decreases with ϕ noticeably when $\phi \geqslant 45°$.

The test results for pull-out from a high strength HCP matrix are summarized in Table 1 along with corresponding results for normal strength matrix. Insignificant difference exists between loads of $\phi = 0°$ from the two matrices, suggesting that the increase in matrix strength does not substantially change the fibre/matrix bond strength. However, the load increase for $\phi = 60°$ is very impressive for high strength HCP matrix, which increase is more than twice the increase for normal strength HCP matrix. This increase is primarily due to the higher resistance to matrix spalling of the high strength HCP matrix. Since the matrix spalling reduces the fibre capability in pull-out resistance and energy absorption, it is expected that the increase in matrix strength using high strength concrete technology can further improve the mechanical behaviour of FRC which exhibits fibre pull-out. However, it should be noted that a matrix with higher strength may also require a higher critical fibre volume fraction for performance improvement.

For the purpose of studying the snubbing friction effect, it is more logical to compare the loads per unit pull-out length for varying inclining angles, because the effective pull-out length decreases with ϕ (as shown in Fig. 6). This is shown in Fig. 7 in which the 'Normalized Load', $\hat{P}$, is defined as the ratio of the maximum load (P_{max}) to the corresponding pull-out length (L_1) at given angle ϕ, normalized with the same ratio for $\phi = 0$:

Table 1. Effect of matrix strength on pull-out load of nylon monofilament

	Pull-out load (*N*)	
	Normal strength HCP	High strength HCP
$\phi = 0°$	4.9136 (CV = 5.6%)	5.2208 (CV = 22.8%)
$\phi = 60°$	11.8483 (CV = 27.1%)	26.9382 (CV = 5.4%)
$P_{60°}/P_{0°} =$	2.41	5.16

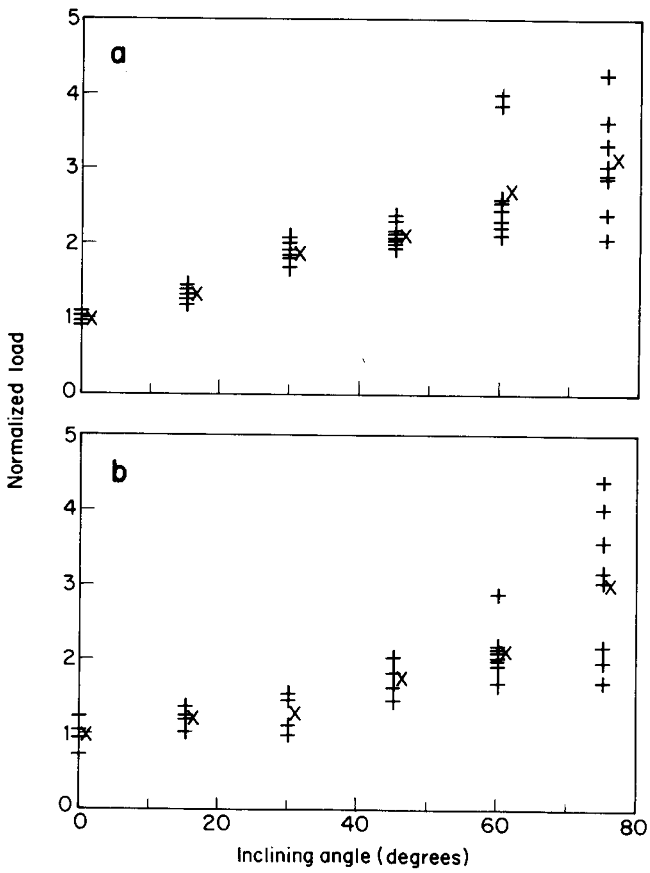

Fig. 7 Normalized load ($\hat{P}$) *vs* inclining angle (ϕ): (a) nylon; (b) polypropylene. '+' indicates individual test data and '×' indicates the group average

$$\hat{P} = \frac{(P_{max}/L_1)_\phi}{(P_{max}/L_1)_{\phi=0}} \tag{1}$$

Since the increase of $\hat{P}$ with ϕ is due to the frictional force at the fibre exit point, it is possible that $\hat{P}(\phi)$ relationship can be characterized by a snubbing friction coefficient, f:

$$\hat{P} = e^{f}\phi \tag{2}$$

or

$$f = \frac{1}{\phi}\ln(\hat{P}) \tag{3}$$

From Equation (3), the friction coefficients for nylon and polypropylene fibres/cement matrix systems can be evaluated and they are presented in Fig. 8. The average values of f are 0.994 for nylon fibre and 0.702 for polypropylene fibre. $\hat{P}$ *vs* ϕ relationships calculated

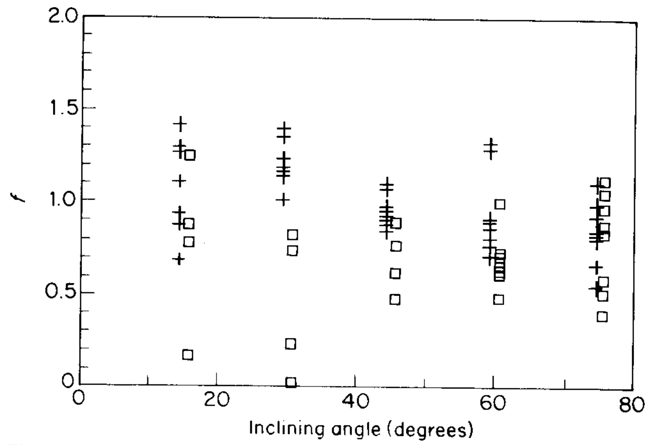

Fig. 8 Friction coefficient (f) *vs* inclining angle (ϕ). +, nylon; □, polypropylene

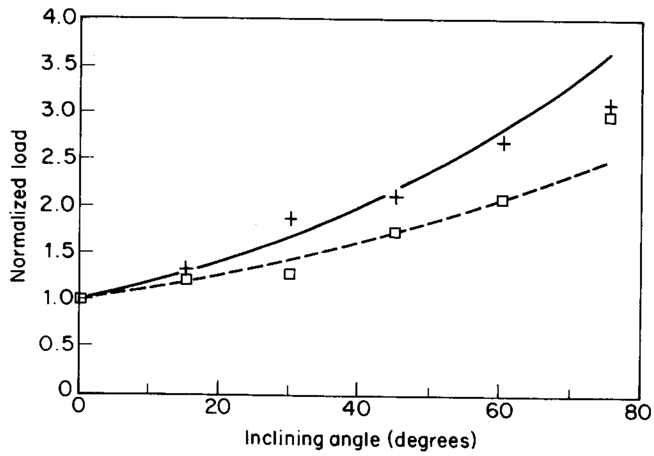

Fig. 9 Comparison between exponential fit curves (solid and broken lines) with experimental data ('+' and '□') for the pull-out load: solid line and '+', nylon; broken line and '□' polypropylene

from Equation (2) using these f values are compared in Fig. 9 with the experimental data. It can be seen that the effect of fibre pull-out at an angle on the pull-out load can be represented in a simple form by a snubbing friction coefficient. This representation will be used in a tensile constitutive model for FRC exhibiting fibre pull-out in fracture.

EFFECT OF FIBRE BUNDLING AND SURFACE MODIFICATION ON PULL-OUT BEHAVIOUR

Fibre reinforcement in the form of bundles is not desirable because the fibre reinforcing capacity is not fully utilized and weak spots may be introduced by the fibre bundles. Fibre bundles are frequently observed as the dominant form of fibre distribution in some FRC composites containing certain fibres, such as glass[4,5] and aramids.[6,7] Although fibre bundling sometimes can be advantageous to increase the energy absorption by allowing some fibre pull-out which might not be possible if the fibres were separated, a direct modification of the fibre/matrix bond property towards the same goal is more effective and thus more desirable. An initial investigation of the effect of fibre bundling on the pull-out behaviour was conducted with Kevlar 49, Spectra 900, and nylon fibres. It was also shown that the fibre/matrix bond property can be modified by fibre surface coating and/or mechanical crimping.

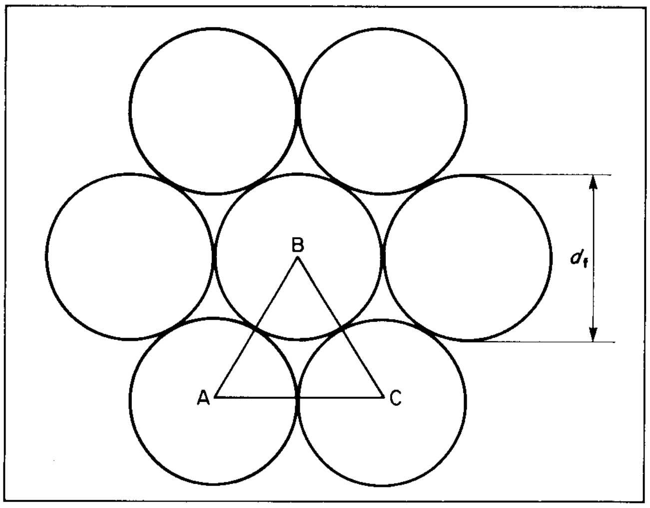

Fig. 10 Unit triangular element in a hexagonally packed bundle

Theoretical consideration of a hexagonally packed bundle

For a closely packed fibre bundle embedded in a cement matrix, the *exposed surface area* of the fibre bundle in contact with the cement matrix is less than the *total fibre surface area*. The volume fraction of fibres, V_f, in the bundle can be calculated by considering a unit triangular element shown in Fig. 10:

$$V_f = \frac{\text{Overlapped areas}}{\text{Area ABC}} = \frac{\frac{1}{2}\frac{\pi}{4}d_f^2}{\frac{1}{2}d_f^2 \sin 60°} = 0.907 \qquad (4)$$

where the overlapped areas are the areas of fibre cross sections *inside* the triangular element ABC. For a large bundle containing N fibres (say, $N > 100$), the cross sectional area of the bundle is:

$$\pi R^2 = \frac{0.25\pi d_f^2 N}{V_f} \qquad (5)$$

Thus R, the radius of the fibre bundle, can be obtained from:

$$R = \sqrt{\frac{N}{V_f}}\frac{d_f}{2} \qquad (6)$$

For a fibre bundle of unit length, the total fibre surface area, A_{total}, is:

$$A_{total} = \pi d_f N \qquad (7)$$

Since the exposed surface of the fibre bundle is composed of hemicircular cylinders (Fig. 11), the ratio of the circumference of a semicircle ($0.5\pi d_f$) to its

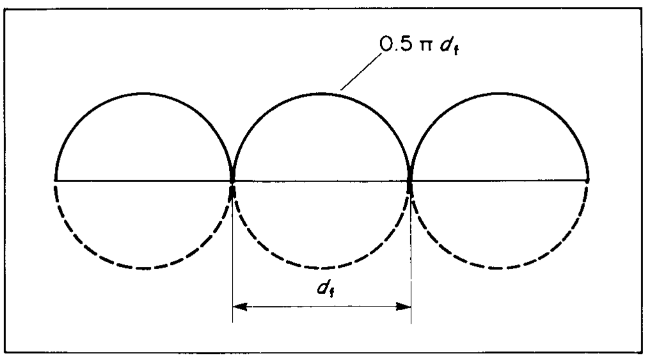

Fig. 11 Surface roughness of a large bundle

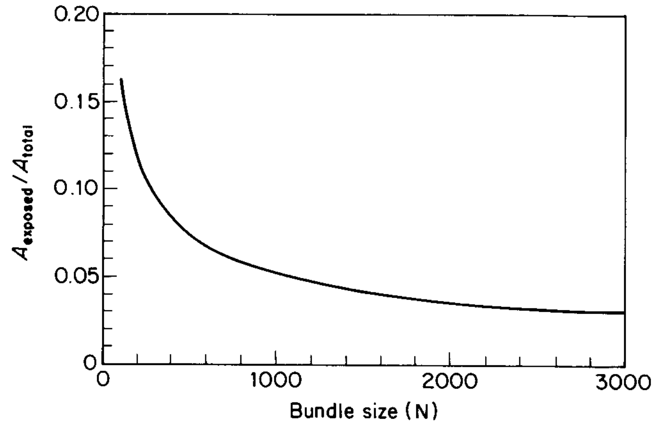

Fig. 12 $A_{exposed}/A_{total}$ ratio *vs* bundle size for a large fibre bundle

diameter (d_f) represents the bundle surface roughness. The exposed area of the bundle, $A_{exposed}$ is given by the circumferential length of a cylinder of radius R multiplied by that ratio:

$$A_{exposed} = 2\pi R \; \frac{0.5\pi d_f}{d_f} = \pi^2 R \qquad (8)$$

The fraction ratio of the exposed bundle surface area to the total fibre surface area can therefore be determined from Equations (6)–(8), given by:

$$\frac{A_{exposed}}{A_{total}} = \pi \frac{R}{d_f} = \frac{\pi}{2} \frac{1}{\sqrt{V_f N}} \qquad (9)$$

and plotted against the bundle size N in Fig. 12. The $A_{exposed}/A_{total}$ ratio given by Equation (9) represents the relative pull-out load of a large fibre bundle in comparison with the load when the fibres are separated and uniformly aligned in the matrix, assuming that the fibre/matrix bond strength is constant, the fibres are pulled out without rupture, and no hydration products penetrate through the fibre bundle.

Specimen preparation and testing

1. *Bundle pull-out tests*

The procedures of specimen preparation and testing of fibre bundle pull-out from the cement matrix of normal strength HCP were the same as for the angle effect tests with $\phi = 0$ and embedded length of 25 mm, described earlier except that a fibre bundle was used in place of the monofilament, and that the fibre bundle was straightened and aligned in proper direction with a special wire tool after filling in the moulds with cement slurry. Yarns of nylon, Kevlar 49 (both manufactured by the DuPont Company) and Spectra 900 (a high strength polyethylene made by Allied Corporation) were used in this study. Information on fibre diameter (d_f), breaking strength (σ_f^u) and bundle size will be provided later with the test results in Table 2. The bundle diameters (d_b) given in the Table were calculated based on the assumption that the fibres were hexagonally packed in the bundles. However, it should be mentioned that the cross sections of the fibre bundles tested were not circular in shape and the fibres were not closely packed, due to the lack of lateral cohesion among the fibres. Fig. 13 shows the typical pull-out load *vs* displacement curves

Table 2. Results of bundle and single fibre pull-out tests

Fibre	d_f (μm)	σ_f^u (GPa)	τ_{single} (MPa)	Bundle size	d_b (mm)	$\bar{\tau}_{bundle}$ (MPa)	$\bar{\tau}_{bundle}/\tau_{single}$
Nylon	27	1.0	0.16	220	0.42	0.051	0.321
Kevlar 49	12	3.0	4.50	1000	0.40	0.198	0.044
Spectra 900	38	2.6	1.02	20		0.328	0.322
				40		0.502	0.492
				57		0.505	0.495
				118	0.43	0.352	0.352

NB: Each stress value represents a test of five samples

2. *Fibre/matrix bond strength for single fibre pull-out*

The average fibre/matrix bond strength for a single fibre pull-out was measured. Such bond strength for the nylon fibres has been determined previously to be 0.16 MPa.[8] The methods in Reference 8 for bond strength measurement were used for Spectra 900 and Kevlar 49 fibres. The bond strength of Spectra 900 fibres was measured by pull-out of fibres embedded through a matrix section with a width of 19.5 mm, as shown in Fig. 14. The bond strength of Kevlar 49 fibres was determined by an indirect method,[8,9] illustrated in Fig. 15 from which the fibre critical length of pull-out, L_c, was measured. L_c, defined as the maximum fibre embedded length for a fibre to be pulled out from a matrix without rupture, is related to the fibre breaking stress σ_f^u and the fibre/matrix bond strength τ by:

$$L_c = \frac{d_f \sigma_f^u}{4\tau} \qquad (10)$$

The bond strength for single fibre pull-out, τ_{single}, can thus be calculated from L_c using:

$$\tau_{single} = \frac{d_f \sigma_f^u}{4L_c} \qquad (11)$$

The results of fibre bundle pull-out tests expressed in terms of average shear stress, $\bar{\tau}_{bundle}$, based on the total fibre surface area A_{total} are presented in Table 2 along with the fibre/matrix bond strength from single fibre pull-out tests, τ_{single}. It needs to be pointed out that

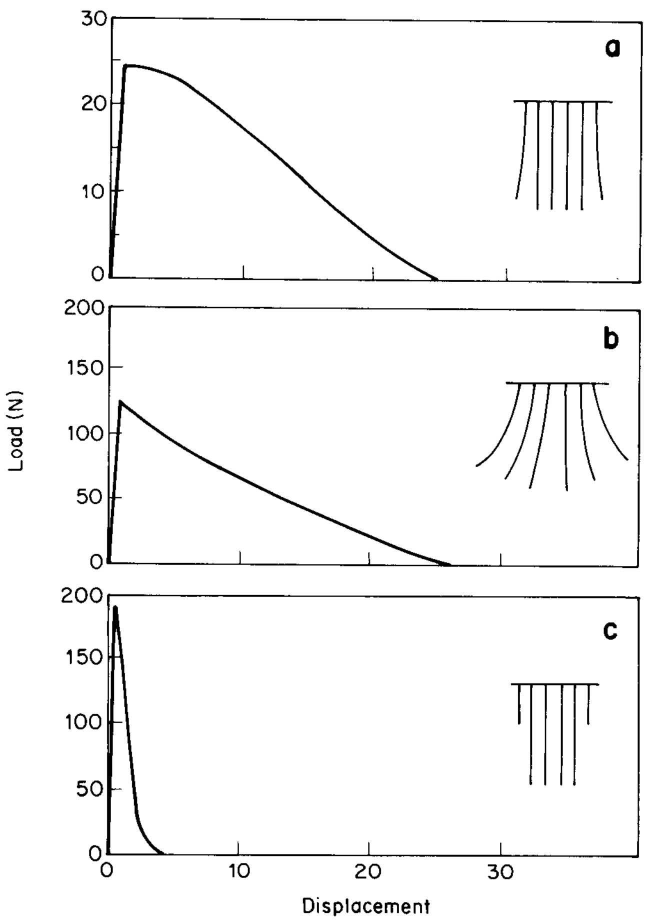

Fig. 13 Typical load-displacement curves for fibre bundle pull-out tests: (a) nylon, $N = 220$; (b) Spectra 900, $N = 118$; (c) Kevlar 49, $N = 1000$. N = bundle size

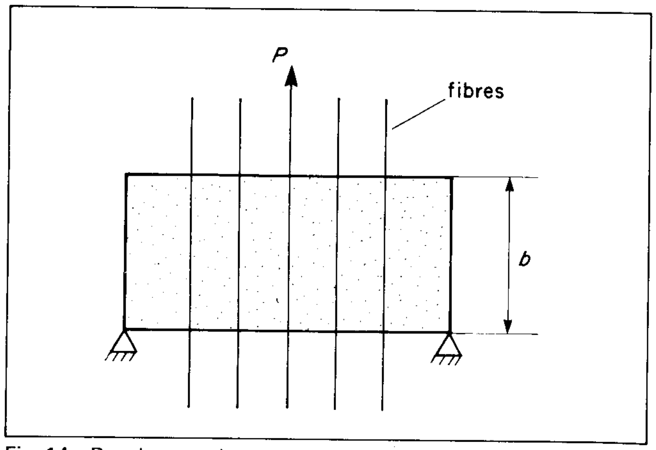

Fig. 14 Bond strength measurement by direct pull-out of a single filament. $b = 19.5$ mm

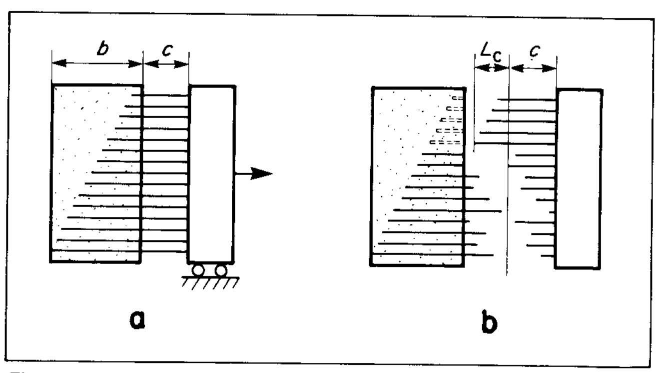

Fig. 15 Determination of fibre critical length of pull-out. (a) Before pull-out; (b) after pull-out. $b = 19.5$ mm, $c = 10$ mm

$\bar{\tau}_{bundle}$ for Kevlar 49 bundles was formally calculated based on the maximum load which corresponded to the rupture of fibres in the outside layer of the bundle. Therefore τ_{bundle} is not a meaningful indication of the fibre/matrix bond property for Kevlar 49 fibres.

3. *Pull-out tests on monofilaments with surface treatments*

The specimen configuration and test procedure for surface treated monofilaments pull-out were the same as for the angle effect tests with $\phi = 0$ and embedded length of 25 mm. The same nylon fibre and matrix (normal strength HCP) were also used. Before putting into the specimens, the nylon filaments were treated in four different ways:

1) heat relaxed only, no special surface treatment applied;
2) heat relaxed then coated with fluorocarbon dry lubricant (a mould release compound);
3) crimped by running through a pair of loosely engaged gears, then coated with fluorocarbon dry lubricant; and
4) crimped by running through a pair of loosely engaged gears, no surface coating.

The crimping action imposed periodic lateral crushes to the fibre, at a frequency of 8 crushes over a 25 mm

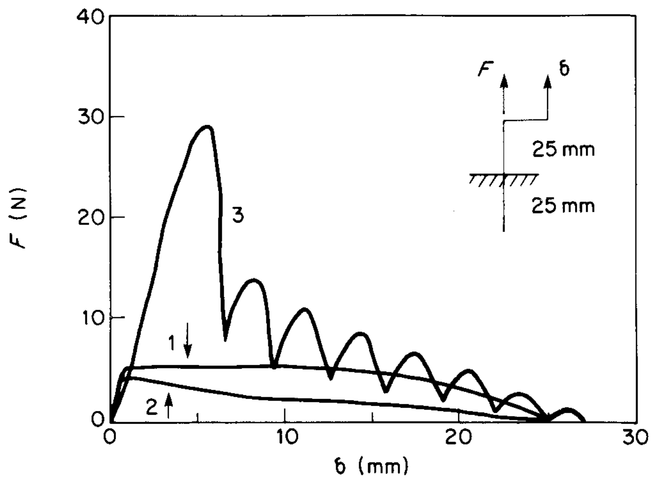

Fig. 16 Photograph of a crimped nylon monofilament. The maximum filament width shown in the photograph corresponds to the diameter of the uncrimped filament (0.508 mm)

Fig. 17 Pull-out test curves for nylon monofilaments with different surface treatments: 1, no treatment; 2, coated with fluorocarbon dry lubricant; 3, crimped and coated with fluorocarbon dry lubricant

length. A photograph of a crimped fibre is shown in Fig. 16.

The pull-out load-displacement curves for these treated fibres are given in Fig. 17 where each curve represents a test of six specimens. The initial parts of these curves correspond to the stretching of the fibre, inside and outside the matrix, causing gradual debonding of the elastic bond. The bend-over points terminating the initial linear portions in these curves indicate the completion of elastic debonding. For fibres without special treatment (curve 1), the pull-out load did not drop over a wide range of displacement, due to the increased sliding resistance resulting from abrasion damages to the fibre surface. For fibres coated with fluorocarbon dry lubricant (curve 2), the load decreases almost linearly as the fibre slides out, suggesting a constant frictional bond strength after complete debonding. For crimped fibres coated with fluorocarbon dry lubricant (curve 3), the maximum pull-out load is very high due to mechanical interlocking. After the maximum load, the load drops sharply and then decreases gradually with a periodic oscillation corresponding to the crimp period. The pull-out curve for fibres crimped without coating is not included in Fig. 17 because in these tests the fibres ruptured at a consistent load of 80 N at the exit points from the matrix, indicating an even higher effective bond strength than that for the crimped fibre with coating.

The relative energy absorptions in the pull-out tests for the first three cases are, respectively, 1, 0.44 and 2.2.

Discussion on theoretical and experimental results

The effect of fibre bundling in FRC is very hard to characterize quantitatively. The difficulties lie in the unknown quantities: (a) the bundle size distribution; (b) the compaction density of the fibre bundles; and (c) the degree of cement penetration into the fibre bundles.

For closely packed fibre bundles, the ratio of the exposed bundle surface area $A_{exposed}$ to the total fibre area A_{total} is equivalent to the ratio of $\bar{\tau}_{bundle}/\tau_{single}$, assuming that the fibre/matrix bond stress is constant and that the bond strength is low enough to allow fibre pull-out without rupture (embedded length $< L_c$). Under these assumptions, Fig. 12 suggests that for a bundle containing 1000 fibres, $A_{exposed}/A_{total} \approx 0.05$ so that the pull-out resistance can be improved by approximately 20-fold if the fibres were well dispersed.

In the experimental study with nylon and Spectra fibres, both having low bond strength with cement matrix, the fibre bundles were not ideally packed and some cement slurry penetrated into the bundle. As a result, the measured ratio of $\bar{\tau}_{bundle}/\tau_{single}$ was much higher than that predicted by theory for closely packed bundles. In addition, $\bar{\tau}_{bundle}$ from tests of Spectra fibres did not change significantly over a range of fibre bundle sizes.

When the fibre/matrix interfacial bond strength is high enough to prevent fibres from pull-out without rupture (embedded length $> L_c$), only a small amount of energy is absorbed if the fibres are individually distributed, as the energy absorption comes solely from fibre rupture work rather than from pull-out. For closely packed bundles, however, only the fibres in the outside layer of the bundle can develop full bond with the cement matrix and will be ruptured during pull-out. The fibres inside the bundle would be pulled out and higher energy absorption due to pull-out can be achieved. This effect has been referred to as the 'telescopic' mode of pull-out.[10] This mode of pull-out was observed in Kevlar 49 bundle pull-out where the fibres in the outside layer were ruptured and the 'sub-bundle' composed of fibres in the inner layers was pulled out. Because of the lack of cement penetration into the bundle, however, the 'sub-bundle' after pull-out was fairly clean and the pull-out resistance was low.

Although it seems that the use of fibre bundle reinforcement is advantageous over individual fibre reinforcement in the case with high fibre/matrix bond strength, to use fibre bundles as reinforcement units is not a preferred way of achieving higher energy absorption. In essence, the telescopic pull-out is derived from the deduction and variation in the fibre/matrix bond strength due to the compaction of the fibre bundle. More desirably, the fibre/matrix bond strength should be modified directly and the fibres should be uniformly distributed such that each fibre can be pulled out without rupture. This has the advantage of efficient use of fibres since all the fibres are pulled out and contributing to the energy absorption, and the advantage of not introducing weak spots often associated with fibre bundles.

For certain aramid FRC in which most of the fibres are in bundle form, it has been observed that the FRC tensile strength can be improved by as much as 90%.[7] Fractographic observation reveals a different mode of failure involving crack deflection around or along fibre bundles in the composites, instead of fibre pull-out or rupture. This indicates the positive influence of bundle reinforcement on FRC tensile strength. However, strength improvements can often be more efficiently obtained through the use of a high strength matrix rather than using fibre bundles.

For optimal use of fibre reinforcing potentials in FRC with one-dimensional fibre distribution, the fibre length should be twice the fibre critical length of pull-out, L_c, which is a function of fibre diameter d_f, strength σ_f^u, and the bond strength τ as given by Equation (10). This ensures that all fibres bridging a matrix crack will be pulled out so as to absorb maximum amount of energy and at the same time the fibre strength is also fully used. For FRC with random (3-dimensional) fibre distribution, the fibre length should be close to L_c instead of $2L_c$ to account for the load increase when the fibres are pulled out at angles discussed earlier. This is demonstrated in a detailed calculation of composite fracture energy as a function of L_f/L_c in Li *et al.*[11] They found in a specific calculation that the fracture energy peaks at $L_f = 1.4L_c$ for $f = 0.7$ and at $L_f = 1.2L_c$ for $f = 1.0$. As indicated by the results of pull-out test of monofilaments with different surface treatments, it is possible to modify the fibre/matrix bond property by surface coating, mechanical crimping, or both. Other ways of fibre surface modification such as plasma treatment should also be explored. Special fibre coating materials are needed which permit good fibre dispersion in cement slurry, have good fastness so as not to be removed from the fibre surface during mixing, and result in a fibre/matrix bond strength desired.

CONCLUSIONS

In FRC containing randomly distributed fibres, almost all fibres are lying at certain angles to the load direction. Being not aligned in the load direction can actually increase the fibre resistance to crack opening during the fracture of FRC. An experimental investigation of the effect of fibre pull-out at an angle has been conducted. Generally, the force and energy of fibre pull-out increase with the inclination angle, but the increases are limited at high angles due to matrix spalling. It was found that the effect of fibre pull-out at an angle on the pull-out load can be reasonably represented by a snubbing friction coefficient. As indicated by the test results, further improvement on the properties of the composite may be expected when high strength concrete is used to reduce the matrix spalling.

The study on effects of fibre bundling and fibre surface treatments indicates that fibre bundling decreases the effectiveness of fibre reinforcement. Optimal utilization of the reinforcing fibres can be obtained when individual fibres are uniformly distributed in the matrix and when the fibre/matrix bond property and fibre size (length, diameter) are properly selected. It is shown that the bond property can be modified by fibre surface coating, mechanical crimping, or both.

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