Filament fracture within glass fibre strands in hybrid fibre cement composites

M. KAKEMI
Research Centre, Asahi Glass Co Ltd, 1150 Hazawa-Cho, Kanagawa-Ku, Yokohama 221, Japan
D. J. HANNANT, M. MULHERON
Civil Engineering Department, University of Surrey, Guildford GU2 5XH, UK

In the study of hybrid fibre cement composites containing continuous polypropylene fibres and glass fibres, it is important to know the fracture behaviour of the glass fibre strand in order to minimise the discrepancies between experiment and theory. A new technique of light transmission through the glass fibres has been developed in order to obtain independent information about the failure of individual glass filaments within a strand. The technique gave quantitative results showing that in the hybrid composite, about 80% of the glass filaments were broken somewhere in the strands before the maximum stress in the composite was reached. This was in contrast to the composite reinforced with glass fibres alone where only about 30% of the filaments were fractured before the ultimate stress. The fractures of the glass filaments in the hybrid composite were more evenly distributed than in the singly reinforced composite which enabled greater strains to be achieved in the hybrid composite at the maximum stress.

1. Introduction
When cement composites are reinforced with glass fibres, the fracture behaviour is controlled by the bond strength at the interface between the fibre bundle and the cement and also by the fracture of individual filaments within the bundle at stresses near to the ultimate stress in the composite [1]. The same applies to hybrid composites containing continuous polypropylene networks and continuous glass strands, the theory for which has been developed by Kakemi [2, 3]. In a previous paper [4] glass filament fracture was examined by dissolving the cement matrix after testing to various strains in uniaxial tension, and using microscopic observation of the exposed strands. However, this yielded little information about the glass filament fracture process and did not give quantitative data of use to a theoretical analysis. A prototype light transmission technique was also described in [4].

In this paper, a more sophisticated light transmission system is described which allowed a quantitative assessment to be made of the process of progressive glass filament failure in the hybrid composite which has shed new light on the synergistic interaction between fibres of widely differing strength and elastic modulus.

Light transmission techniques using optical fibres for monitoring structures are now well developed [5–12]. However, alkali resistant glass fibres as used in cement products, contain several kinds of oxides such as Al_2O_3, ZrO_2, CaO and Na_2O and the intensity of transmitted light is reduced by these oxides [13] so that light can only be easily transmitted over distances of a few centimetres.

Light transmission in glass fibre cement composites has previously only been achieved in lengths of 7 mm [14–16] but in order to measure filament fractures in tensile specimens, a transmission length of about 80 mm is required resulting in the development of the equipment described below.

2. Experimental
2.1. Specimen manufacture
The samples were made by hand lay-up of five layers of polypropylene networks comprising 4% by volume with a single layer of 0.6% by volume of continuous glass fibre strands positioned 2–3 mm from the base of a 6 mm deep mould (see Fig. 1). The glass fibres were slightly tensioned to keep them as straight as possible in the mould.

The matrix consisted of ordinary Portland cement, pulverised fuel ash, sand passing a 300 micron sieve and superplasticiser in the weight proportions 1 : 0.25 : 0.19 : 0.016. The total water/cement ratio was 0.34. After curing for 20 hours in air, the composite was cured under water for 28 days before being cut with a diamond saw into strips about 85 mm long by 15 mm wide for the light transmission tests.

2.2. Light transmission technique
The cut ends of the specimens which were to be the illuminated surface and the observed surface, were required to be flat and parallel to obtain uniform transmission of light. One end of the specimen was buried

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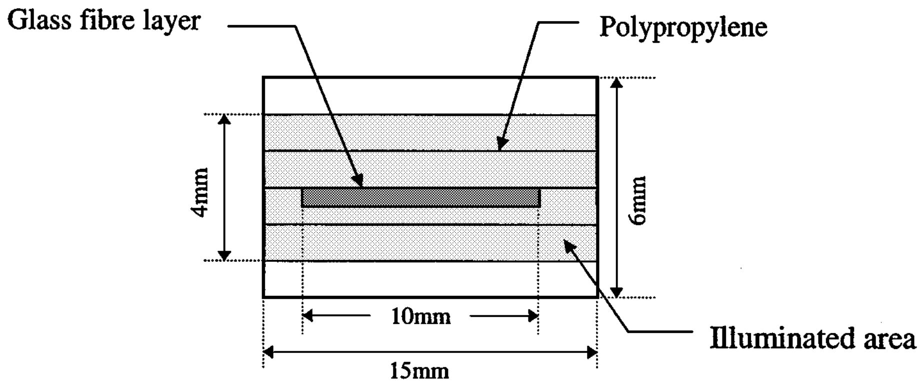

Figure 1 Fibre arrangement in the composite showing illuminated area.

vertically in epoxy resin and then polished with progressively finer grits with final polishing with 1 micron DUR lubricant, after which the other end was treated in the same manner.

In this test, a significant quantity of light is required in a very small area. In spite of this requirement, heat must not be allowed to affect the specimen under examination. A KL1500 (Schott Ltd) cold light source was used to illuminate the specimen since the thermal component of the energy from the halogen lamp is filtered out and only the visible light is passed through optical fibres. The maximum illumination at light outlet is approximately 10 Mlx.

Light was passed into the specimen via a light neck with a rectangular light area 15 mm by 4 mm giving the illuminated surface shown in Fig. 1. The specimen under test was inserted into a metal holder and the light neck was connected to the holder at the lower end (Fig. 2). The specimen was held vertically and touching the end of the light neck. Using this arrangement, the same intensity of light at any position in the specimen could always be obtained. Transmitted light was observed on the opposite end of the specimen using a stereoscopic microscope (Olympus SZ300300) with camera attachment. The microscope could be moved vertically and horizontally with precision to allow both visual examination and photography of all the glass fibres on the cross section.

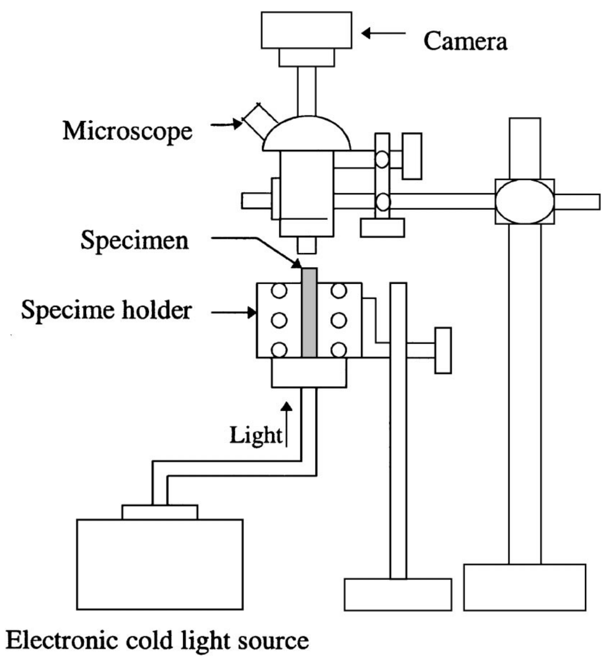

Figure 2 Equipment for the light transmission test.

The test was carried out in a dark room. Since the intensity of the light transmitted along the glass fibre through the composite was rather weak, a high speed film, ASA 3200, was used. It was found that normal film (ASA 125) required an exposure of 5 minutes whereas the ASA 3200 film produced good results with an exposure of only 5 seconds.

Before the tensile tests, the continuity of the fibres was confirmed by checking that every glass fibre filament in a strand could transmit the light. Although the intensity of transmitted light through individual filaments was not uniform, each filament could be clearly discerned.

2.3. Tensile tests

Uniaxial tensile tests were carried out in an Instron 1122 test machine with a cross-head speed of 2 mm/min. Fig. 3 shows the test specimen with a 40 mm gauge length clip-on extensometer with strain measured by linear variable differential transformers (LVDTs). All the data of load and strain were recorded simultaneously by a computerised data logger and two X-Y recorders with different scales.

After the initial condition of transmitted light was observed, tensile tests were carried out with the specimen being unloaded for observation at various strains as decided from the stress-strain curve on the X-Y recorder. The transmitted light was then observed, recorded and compared with the initial condition each time. Then the specimen was reloaded in tension. These procedures were repeated until the light passing through the glass fibres had disappeared.

3. Results and discussion

3.1. Stress-strain curves and transmitted light

A representative cyclic stress-strain curve for a hybrid composite reinforced with polypropylene networks and continuous glass fibres is shown in Fig. 4. The specimen was unloaded at three different points, A, B and

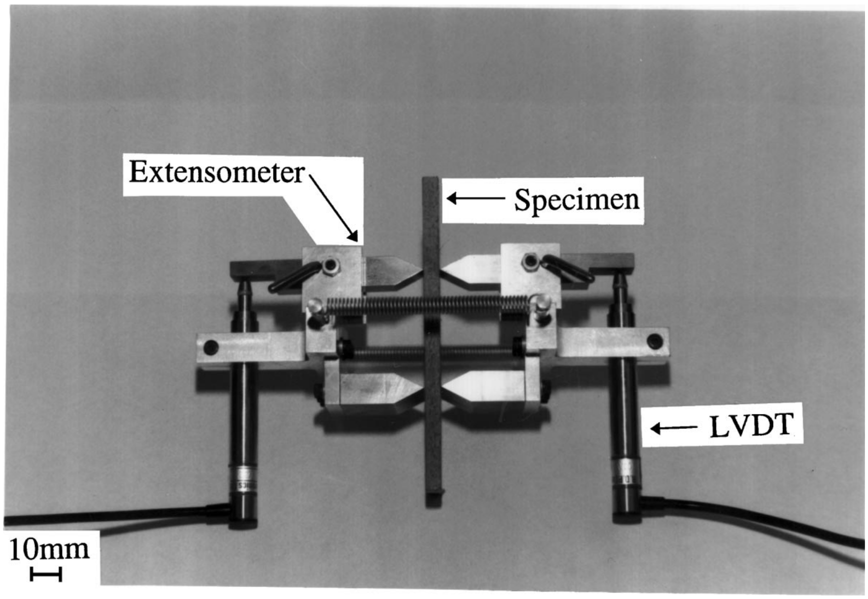

Figure 3 Test specimen with clip-on extensometer using linear variable differential transformers (LVDTs).

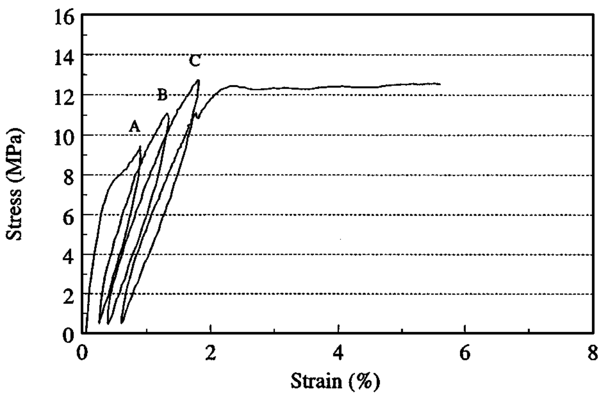

Figure 4 Cyclic stress-strain curve for a hybrid composite reinforced with polypropylene networks and continuous glass fibres.

C in the figure, and the transmitted light was observed. The strain at point A is 0.9% which is just after the multiple cracking region, at which many cracks have been generated in the composite. Point B is at 1.3% strain which is in the region where the continuous glass fibres and the polypropylene networks are stretched linearly with frictional bond. Point C is at 1.8% strain which is just before the point of maximum stress. After unloading at the point C, the stress-strain curve develops into the region dominated by the ductility of the polypropylene networks, where large increase in strain with little increase in stress can be seen.

Typical photographs of individual strands are shown in Figs 5 and 6. It can be seen that, in the initial unloaded condition, the intensity of light is not uniform due to over exposure and under exposure so that it is important that at points A, B and C on Fig. 4, the light transmission photographs are compared with the original condition.

When comparing point A on Fig. 5 with the initial condition, there is little difference between the photographs showing that in the multiple cracking region, the matrix cracks successively without causing much failure of the glass fibres. At point B, the light intensity generally weakens and a part of the transmitted light disappears in some filaments. This is because, after the multiple cracking region, the glass fibres and the polypropylene networks are stretched so that the stress and the strain of the hybrid composite increase and also the failure of some glass filaments is initiated. At the point C just before the maximum stress, a considerable amount of light has disappeared which indicates that many glass filaments are broken somewhere in the composite. Fig. 6 also shows a comparison of the initial condition and point C, again demonstrating a considerable amount of glass fibre fracture.

This light transmission technique does not allow the continuous observation of glass filaments in a strand with increase in strain because unloading at increments and removal from the test machine is required. However, from Figs 5 and 6, it seems that the failure is initiated at the edge of the strand and extends to the inside. This finding is in agreement with the varying bond strengths measured within a strand [17], the greatest resistance to sliding occurring at the outside edge of the strand. Therefore, the characteristics of the glass filaments in contact with the cement matrix are important for the prediction of the tensile behaviour of glass/polypropylene hybrid fibre composites.

3.2. Quantitative analysis of transmitted light

The variation of the transmitted light with increase in strain has been described qualitatively in Section 3.1. In order to predict the maximum stress of the hybrid composite accurately, the failure of the glass fibres during increasing tensile stress should be understood quantitatively. Thus, the areas of the transmitted light in photographs similar to those shown in Figs 5 and 6 were measured as the amount of intact glass filaments by an image analyser, Quantimet 920. These black-and-white photographs have good contrast so that the condition of the transmitted light can be taken directly from the photographs by a video camera to be analysed on the screen

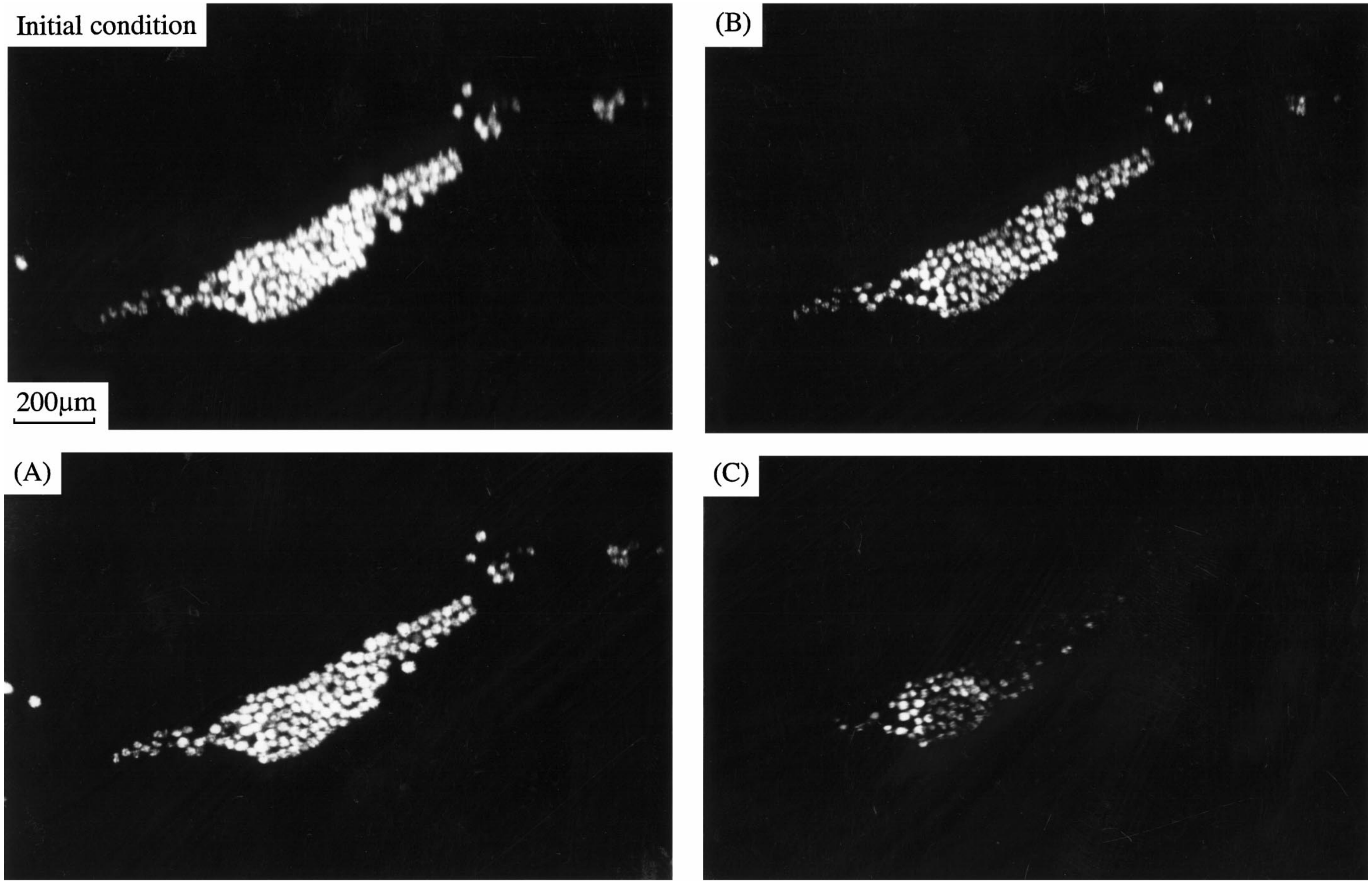

Figure 5 Typical variations of the transmitted light in the glass strand: (A) at point A in Fig. 4, (B) at point B in Fig. 4 and (C) at point C in Fig. 4.

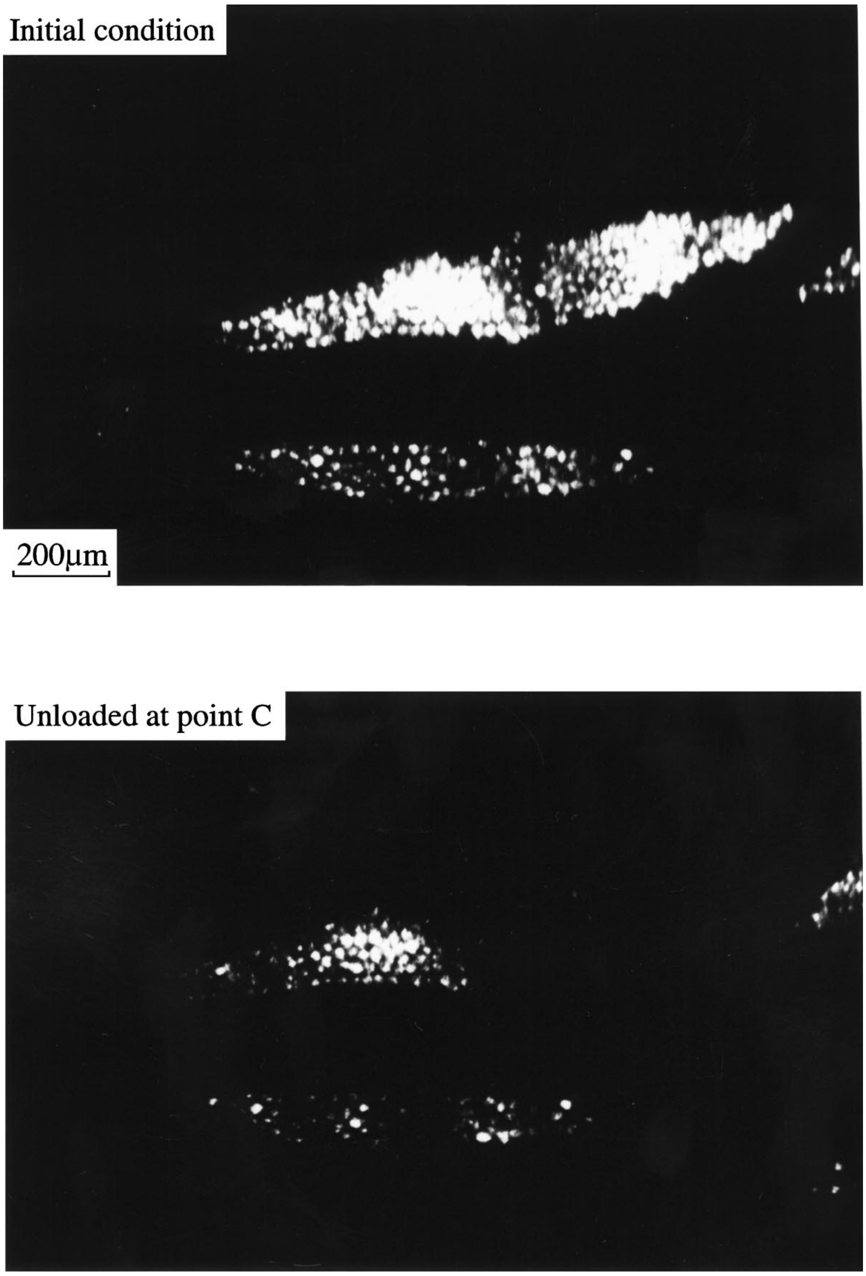

Figure 6 Comparison of the transmitted light between the initial condition and the unloaded condition at point C in Fig. 4.

of the Quantimet. The effects of exposure condition and focusing in the photographs were ignored and the area of the transmitted light was measured. Results of the analysis for one specimen are presented in Table I.

The number of glass filaments was obtained from the measured area of light divided by the cross sectional area of the glass filament (diameter: 14 microns). Since each specimen contains 36 glass fibre strands there are in theory a maximum of 3,600 filaments available to transmit light. In the initial condition, however, the over exposure makes the measured area of the light larger than theoretical area. On the other hand, flaws in the glass fibres, damage during manufacturing and polishing and under exposure make the area of the light smaller. In Table I the calculated initial number of glass filaments was close to the theoretical value; however the calculated numbers for other specimens were often smaller than the theoretical value. For specimens that had been loaded and unloaded, the ratio of intact filaments was calculated from the residual number of visible glass filaments divided by the initial number.

In spite of the fact that about 80% of continuous glass fibres were broken somewhere in the composite just before the maximum stress, the composite still kept its rigidity. If 80% of glass fibres are locally broken at

TABLE I Representative results of the quantitative analysis for transmitted light in all glass strands in one hybrid composite specimen reinforced with polypropylene networks and continuous glass fibres. A, B and C refer to points on Fig. 4

	Initial	A	B	C
Strain (%)	0	0.90	1.32	1.79
Area of light ($\times 10^3\ \mu m^2$)	562	578	449	114
Number of glass filaments	3652	3815	2919	739
Ratio of intact filaments (%)	100	100	79.9	20.2
Ratio of broken filaments (%)	0	0	20.1	79.8

one crack face, the effective intact glass fibre volume is 20% of its actual volume, i.e. $0.6\% \times 0.2 = 0.12\%$, and therefore the hybrid composite should have failed before point C in Fig. 4. Thus, the broken glass filaments are probably distributed between several crack faces because these are the positions at which the fibre stress is a maximum [3]. The hybrid composite summarised in Table I had 23 cracks in the gauge length of 40 mm. Provided that the failure of the glass fibres is uniformly distributed over all the cracks, then $79.8/23 = 3.5\%$ of glass fibres are broken at each crack face, which means that the ratio of effective glass fibre is 96.5% of the actual fibre volume at each crack at C just before the point of maximum stress. However, such a uniform distribution of glass failure is unlikely to occur and therefore, assuming only one fracture per filament, the maximum ratio of broken glass filaments at one crack face must be somewhere between 3.5% and 79.8%, which controls the tensile behaviour of hybrid composites. The same analysis was carried out for single fibre composites reinforced with continuous glass fibres in order to obtain the maximum ratio of broken glass filaments at one crack face related to the ultimate point.

3.3. Comparison between hybrid and single composites

The representative cyclic stress-strain curve of single composites reinforced with 1% of continuous glass fibres by volume is shown in Fig. 7. At points D and E, the specimen was unloaded and the transmitted light was observed under a microscope. Point F is the ultimate point in the cyclic tensile test. The strain at point D is 0.26%, which is just after the multiple cracking region. Point E indicates 0.77% strain, which is an equivalent region to point B on Fig. 4 but strains of 1.03% and 1.52% were also used for point E.

Representative photographs of the transmitted light at points D and E (Fig. 7) compared with the initial conditions are shown in Fig. 8. There are few differences between the initial condition and point D. However, at point E, the intensity of the light has become significantly weaker.

Other specimens were unloaded at 1.03% and 1.52% strain before the ultimate point and the observed transmitted light was analysed quantitatively as described in Section 3.2. All the ratios of broken glass filaments at the point E in Table II were approximately 30%. These ratios are plotted against strain of glass/polypropylene hybrid composites and continuous glass fibre reinforced composites in Fig. 9.

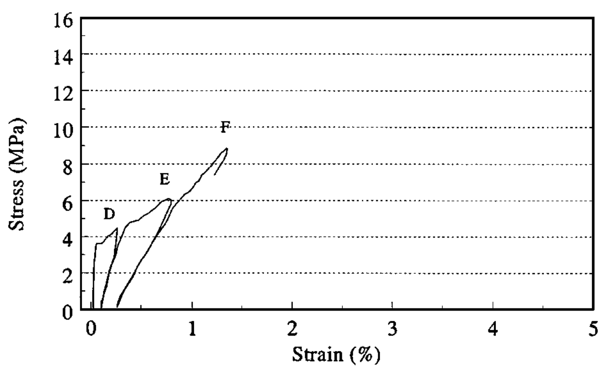

Figure 7 Representative cyclic stress-strain curve for a composite reinforced with continuous glass fibres alone (volume of glass fibres = 1.0%).

TABLE II Results of the quantitative analysis for transmitted light in composites reinforced with continuous glass fibres alone (D and E refer to points on Fig. 7)

		Initial	D		E	
Strain (%)		0	0.26	0.77	1.03	1.52
Number of glass filaments	No. 1	3866	3065	2570	—	—
	No. 2	3302	—	—	2733	—
	No. 3	2202	—	—	—	1461
Ratio of intact filaments (%)		100	79.3	66.5	68.8	66.3
Ratio of broken filaments (%)		0	20.7	33.5	31.2	33.7
Number of cracks				8	9	9

As shown in Fig. 9, in glass fibre single reinforced composites, the glass failure begins at strain lower than 0.26% which is considerably less than for the hybrid composites. The ratio of broken glass filaments is almost constant at about 30% from 0.7% strain to 1.5% strain. The glass fibre reinforced composites described in Table II had 8 or 9 cracks in the 40 mm span and provided that the failure of the glass fibres is distributed uniformly over all cracks, the average percentage of broken filaments at each crack face at 1.52% strain is $33.7/9 = 3.7\%$. Thus, the maximum percentage of broken glass filaments at one crack is somewhere between 3.7% and 33.7%.

It is always difficult to know the true value of glass fibre strength in a cement composite due to possible damage to the glass during sample manufacture or alkali attack. Nevertheless, the glass manufacturer's quoted glass strength (1500 MPa) was used to compare the measured strength of the glass reinforced cement single composite with the calculated value, for a volume fraction of 0.01 i.e. $0.01 \times 1500 = 15$ MPa. Table III shows this comparison for the three samples used for light transmission experiments, the average value of experimental/calculated stresses being 70%. This ratio is close to the percentage of intact filaments in Table II which provides some support to the suggestion from the light transmission studies that the maximum percentage of broken filaments at one crack before final fracture is 30%.

TABLE III Ultimate tensile stress and ratios of experiment/calculated stresses for continuous glass fibre reinforced composites. Volume of glass fibre 1.0%

No.	Experimental ultimate stress (MPa)	Experiment/calculated
1	8.83	0.59
2	11.93	0.80
3	10.67	0.71
Average	10.48	0.70

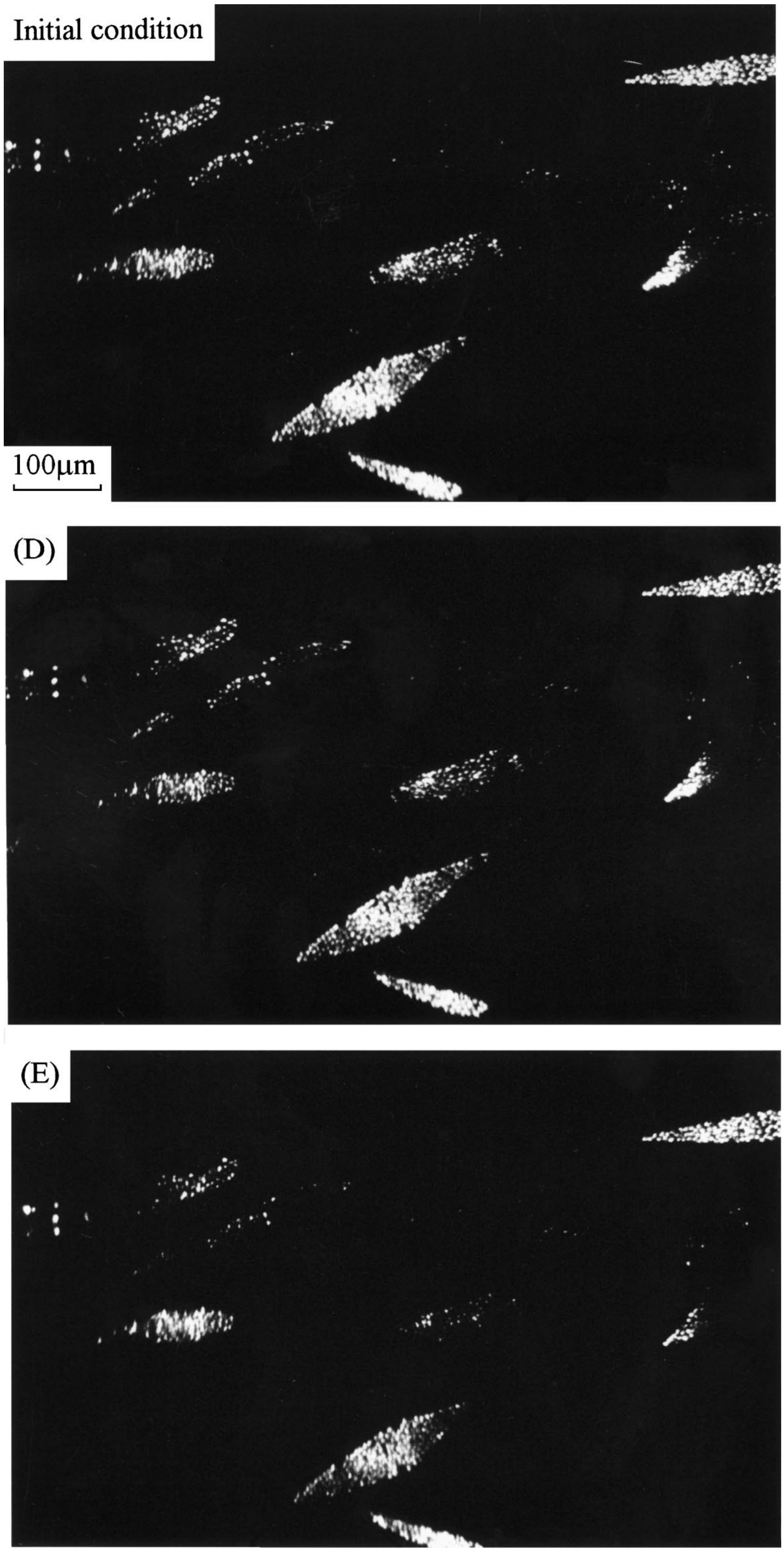

Figure 8 Variations of the transmitted light with increase in strain of the glass reinforced composite: (D) at point D in Fig. 7 and (E) at point E in Fig. 7.

Fig. 9 demonstrates the importance of the polypropylene in enabling the glass fibres in a hybrid composite to sustain greater strains before filament fracture than in single fibre composites. Also, because a proportion of the stress originally carried by the glass filaments before glass fracture is transferred to the polypropylene after glass fracture, the failure of glass filaments is likely to be more evenly distributed along the length of the specimen than in the single fibre composite, with the possibility that several cracks could sustain 30% of filament fracture before the ultimate composite stress is reached.

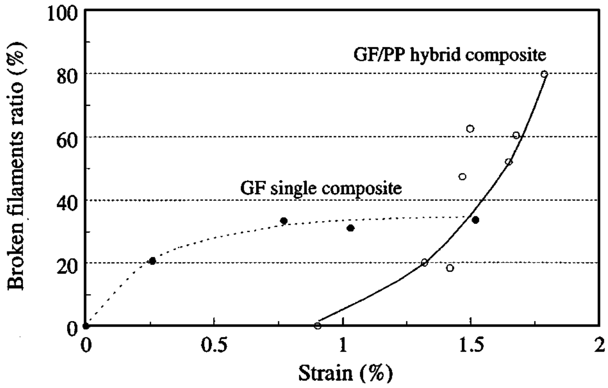

Figure 9 Ratios of broken glass filaments with increase in tensile strain for glass/polypropylene fibre hybrid composites and glass fibre single reinforced composites.

4. Conclusions

A technique of light transmission through alkali resistant glass fibres was developed to enable a quantitative assessment to be made of the fracture of individual glass filaments within a strand as a function of composite strain. In the hybrid composite, about 80% of the glass fibre filaments were found to have fractured before the maximum stress was reached compared with only about 30% for the composite reinforced with glass fibres alone.

The numbers of filaments fractured at individual crack faces could not be observed but, assuming that the manufacturer's strength of 1500 MPa for the glass fibres was correct, the effective glass fibre volume at ultimate stress was calculated to be 70% of the actual fibre volume.

One result of the more evenly distributed filament fracture in the hybrid composites was that more glass filaments were able to sustain greater strains before fracture than in composites reinforced with glass fibres alone.

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Received 31 March
and accepted 14 September 1998