JOURNAL OF MATERIALS SCIENCE 10 (1975) 2124–2133

Flexural fatigue of glass-fibre-reinforced cement

A. P. HIBBERT, F. J. GRIMER
Building Research Establishment, Garston, Watford Herts, UK

Results of a large number of tests on glass-fibre-reinforced cement (GRC) subjected to repeated flexure on a prototype multiple specimen fatigue rig are presented in the form of probability–stress–number of cycles to failure (*PSN*) diagrams. The fatigue limit at 10^6 cycles was found to be approximately 90% of the limit of proportionality determined in static bending. The effect of age, storage conditions and overstressing are reported and some comparisons are drawn between the behaviour of GRC and asbestos cement.

1. Introduction

In recent years considerable interest has been shown in the reinforcement of gypsum plaster and Portland cement with small amounts of glass-fibre for use in partitions, cladding panels, ducting etc [1]. The latter material, GRC, requires the use of alkali-resistant glass (Cem-FIL*) because of the high pH of hydrating cement which causes rapid degradation of the E-glass fibres used extensively in reinforced plastics [2]. Considerable work has been done on the static behaviour of this material, both in tension and bending, and some cyclic tensile tests have been reported [3]. This paper, however, is concerned mainly with the effect of fluctuating stress on GRC type composites made in the form of large sheets (at the Building Research Station) by a spray-suction technique [4].

The behaviour of the material will be dictated by the characteristics of the matrix, the fibre and the fibre–matrix bond. All these will vary, to a greater or lesser extent, with time and the conditions under which the material is cured and stored. Results are, therefore, presented for a range of materials which had been stored under different conditions for various lengths of time.

2. Experimental method

The results of fatigue tests on nominally identical specimens of any material show a large amount of scatter. With a material such as GRC, the ultimate strength of which has a coefficient of variation of approximately 10%, if any meaningful fatigue data are to be obtained a large number of specimens must be tested at each stress level. To achieve this a multiple specimen fatigue rig was developed which was capable of testing up to sixteen specimens simultaneously in four-point bending (Fig. 1). The load was applied to the rig by an hydraulically driven servo-controlled ram fitted to a steel frame and connected to the rig body through a load cell. A pin-jointed framework attached to the base of the frame divided the load equally between the sixteen specimen positions. The loading and support bars were fitted with sleeves running on needle roller bearings to ensure that there was no resistance to flexure of the samples. The loading bars were free to move vertically in recessed channels, the bottoms of which were fitted with rubber inserts to minimize the possible transference of shock loads to the rig when a specimen failed completely. The control equipment ensured that the desired load profile was maintained throughout the test, independent of the amplitude of ram travel, and hence regardless of any changes in the stiffness of the material. Microswitches were positioned at the bottoms of the loading bar channels and complete failure of the specimen resulted in their activation by the loading bar. Each microswitch was connected to a digital clock which recorded the time to failure of the specimen. Unless otherwise stated all the tests

* Registered trade mark of Pilkington Brothers Ltd.

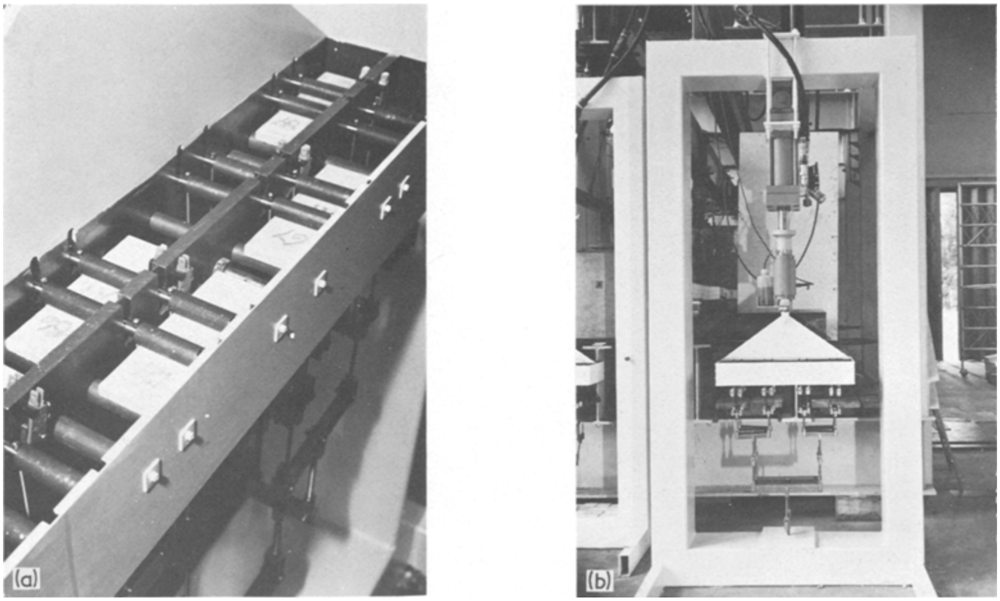

Figure 1 Multiple specimen fatigue rig.

were carried out at a frequency of 3 Hz with the stress varying from zero to a predetermined maximum. In practice it proved necessary to maintain a small load at the minimum of the load cycle but this was so small as to have negligible effect on the results. In all cases the specimen dimensions were 150 mm x 50 mm x 10 mm.

The lives of the individual test pieces in each run were ranked in ascending order of magnitude and a probability of failure, P, assigned to each. This is best given by $i/(n + 1)$, where i is the ith position in the ranked list and n is the number of specimens tested in the run (usually sixteen). The distribution of fatigue lives was assumed to be log-normal since analysis [5] of a sample of 32 failures at the same stress level had shown this to be a reasonable approximation. Using log–probability paper a straight line was drawn by eye through the datum points to give a graph of number of cycles to failure N, against P. The lines were not fitted by least-squares analysis since this is not strictly applicable [6]. A typical *PN* line for

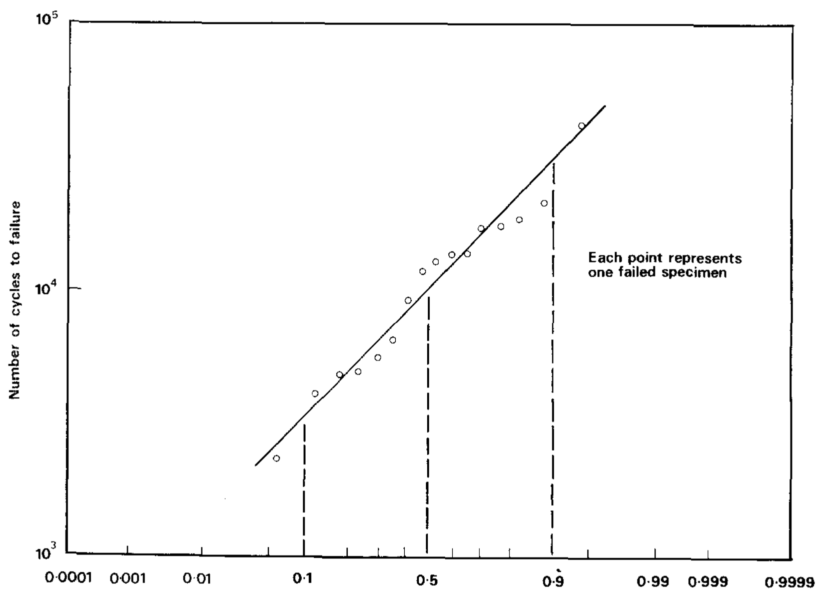

Figure 2 Typical *P–N* line for GRC.

GRC is shown in Fig. 2. It will be noticed that the points are not scattered randomly about the line as in a normal "best straight line" but clustered in groups. This clustering is quite typical of this type of plot and arises from the constraint that $N_{i+1} \geqslant N_i$ for all values of i [6].

A series of runs at different maximum cyclic stresses then enabled the complete *PSN*, (probability–stress–number of cycles to failure), field to be determined.

With the number of specimens tested at each stress level this method gives a very good estimate of the median life but, as with all fatigue investigations, it was difficult to obtain accurate values for the life at the "tails" of the distribution. Though the median life was reproducible to within a few percent of the log-life, the $P = 0.1$ level showed much more variation especially at higher life times; this is a reflection of the inadequacy of the log-normal distribution at the extremes. For this reason comparisons have been drawn between the median lives, i.e. $P = 0.5$, although some $P = 0.1$ lines have been drawn to indicate the scatter of life times that was observed in the material tested.

Since the input load to the rig was divided equally each specimen was subjected to a slightly different stress because of small differences in thickness, an unavoidable consequence of the sheet fabrication processes. The coefficient of variation in stress for a run of sixteen specimens was typically 6% but there was no significant correlation between stress in an individual specimen and its position in the ranked list for the run. One of the main factors contributing to the scatter was local variation in glass content; this is discussed below.

3. Materials

GRC sheets made by the spray-suction process contain a nominal 5 wt% of fibre incorporated in the form of chopped strands of approximately 204, 9 μm diameter filaments each coated with a thin layer of PVA or similar material. The strands are distributed evenly throughout the depth of the board and at random on its plane; their length can be varied from about 10 to 40 mm. The introduction of 5% of fibres in this form imparts a certain amount of pseudo-ductility resulting in a high impact resistance for the material. The matrix may be modified by the addition of pulverized fuel ash (PFA), 40% in this work, which provides a less agressive environment for the fibres; or by the addition of certain polymers which enable a lower water cement ratio to be used during the spray process and also have a beneficial effect on the mechanical properties of the matrix.

The sprayed boards, 1 m × 4 m × 10 mm, were cut after 7 days storage under wet sacking into coupons approximately 150 mm × 50 mm × 10 mm, these were then randomized using a table of random numbers and stored under the conditions described in Table I which also gives details of the composition and properties of the boards tested. The modulus of rupture (MOR) and limit of proportionality (LOP) (the latter may for practical purposes be regarded as the elastic limit or stress at first crack) were determined from slow bend tests on an Instron Testing Machine using the same four-point bending configuration as in the fatigue tests. At least six specimens were tested to obtain the values quoted.

In addition to the GRC boards, some tests were also performed on an asbestos cement sheet typical of the type available commercially. Although these were of a limited nature they do allow some comparisons to be drawn between the fatigue behaviour of the two types of material.

4. Results

The median lifetime *SN* curves for three GRC boards and the asbestos cement sheet are given in Figs. 3 and 4. When projected back to one half cycle the lines are in reasonable agreement with the statically determined MOR values at the time of test although these values were obtained at a much slower rate of loading than that applied in the fatigue tests. At a loading rate equivalent to that of the fatigue tests the MOR may be substantially higher than that reported here. However, fatigue of concrete has been shown to be independent of frequency, and hence stress rate, from 4 to 20 Hz although the MOR may be up to 50% greater than the static value at loading rates equivalent to that applied in cycling at 4 Hz [7].

When cycled with a maximum stress equal to that at the LOP the GRC boards had similar median lives, i.e. in the region 10^5 to 10^6 cycles (Fig. 5).

There is little difference in the fatigue behaviour of specimens whether stored and tested in water after the initial 7 day curing period, or in air (Fig. 6). The better fatigue life at the lower stress of those stored in water is due to an increase

TABLE I

Board	Matrix	Fibre length (mm)	Storage condition	Age at fatigue test (mth)	28 Day				At time of test			
					Mean MOR ($MN\,m^{-2}$)	Coefficient of variation (%)	Mean LOP ($MN\,m^{-2}$)	Coefficient of variation (%)	Mean MOR ($MN\,m^{-2}$)	Coefficient of variation (%)	Mean LOP ($MN\,m^{-2}$)	Coefficient of variation (%)
1	OPC	34	Water	3	–	–	–	–	42.0	5.7	13.2	9.9
2	OPC/40% PFA	22	Water	3	–	–	–	–	23.0	7.0	8.9	13.5
3	OPC	22	Water	9	–	–	–	–	22.0	20.0	11.6	14.0
4	OPC/40% PFA	10	Water	9	19.2	5.8	–	–	21.9	6.9	11.3	6.9
		43	Water	9	23.0	3.7	9.13	9.4	24.0	6.9	10.7	8.5
5	OPC	32	Natural weathering	12	35.4	10.5	–	–	22.0	9.2	–	–
6	OPC/40% PFA	42	Natural weathering	12	35.6	6.1	–	–	29.7	5.2	–	–
7	OPC	32	Air	6	39.4	5.0	11.3	6.9	37.0	4.0	10.2	9.9
		32	Water	6	32.4	6.8	15.9	3.4	27.9	7.4	16.7	1.9
8	Asbestos cement	–	Water	–	–	–	–	–	28.3	2.9	–	–
		–	Air	–	–	–	–	–	37.8	7.7	–	–

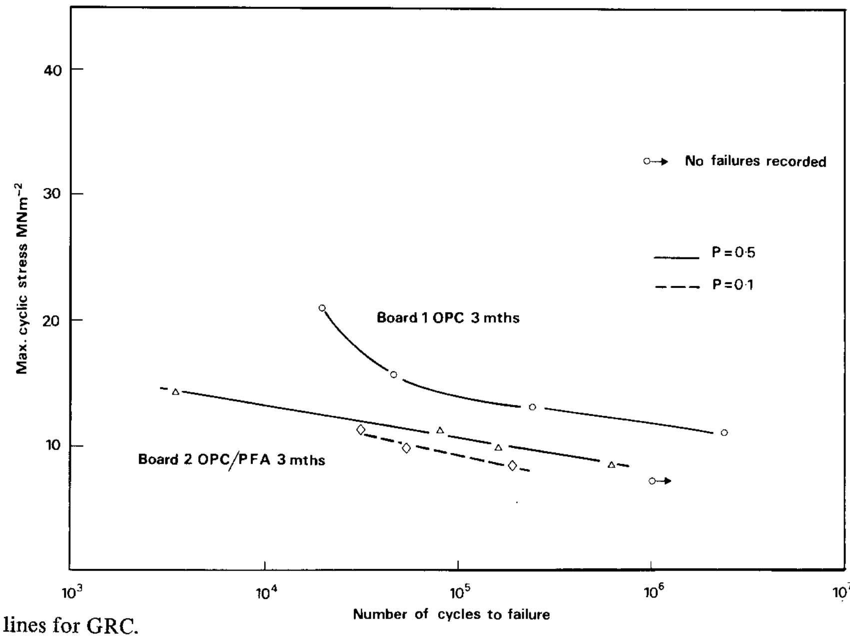

Figure 3 PSN lines for GRC.

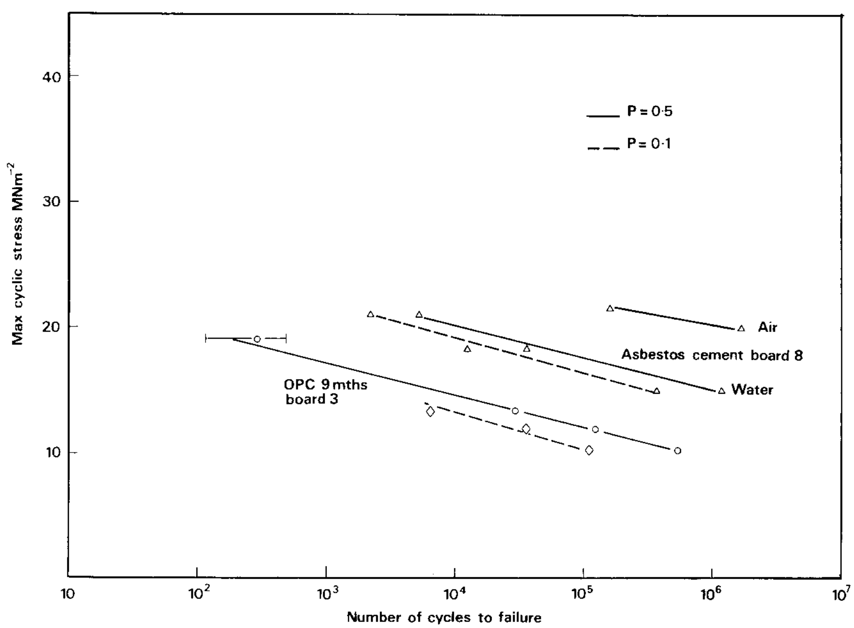

Figure 4 PSN lines for asbestos cement/GRC.

in the LOP resulting from a greater degree of cement hydration. Water stored coupons were sealed in polythene bags with a little water before testing to ensure that they remained completely saturated but it was found that allowing them to dry had negligible effect on either the fatigue life or the static ultimate strengths. Dry stored specimens when saturated in water for several weeks prior to testing showed a slight decrease in both static strength and number of cycles to failure but this was not significant compared with the performance of the asbestos cement sheet used in these tests which exhibited a large change in both these properties with absorbed water (Fig. 4). The fatigue of asbestos cement was also time dependant rather than cycle dependant, in the region 1 to 3 Hz (Fig. 7); an effect which was not observed with GRC. If this time dependence is a real property of asbestos cement and is not confined to the particular board tested here, then it is interesting to note that conventional fatigue testing may considerably over-estimate the life-

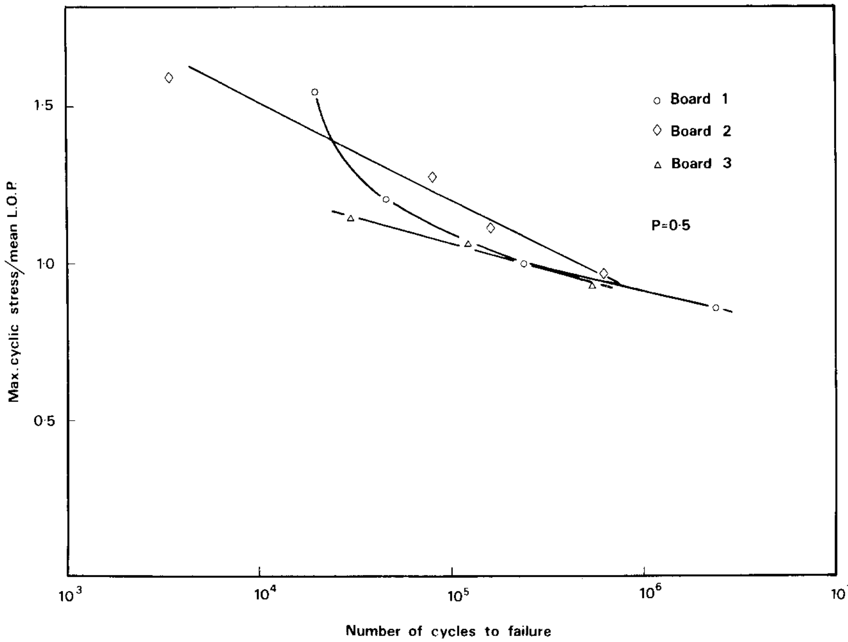

Figure 5 Number of cycles to failure.

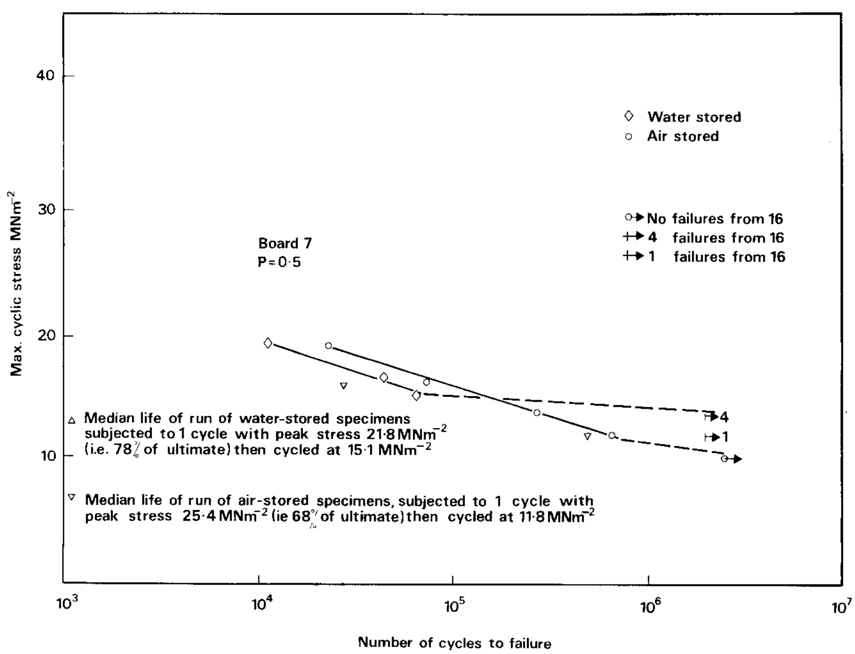

Figure 6 Effect of storage condition and overstressing.

time of a component if it is subjected to only a slow cycling rate. However, the results obtained are of a very limited nature and further work is necessary to confirm this.

The effect of a change in fibre length from 10 mm to 40 mm was found to be negligible in an OPC/PFA matrix (Fig. 8). This was not unexpected since the critical fibre length for such a composite is probably less than 10 mm.

Natural weathering over a period of 1 year resulted in a reduction in the gradient of the PN line consistent with the fall in MOR. There was little difference, however, in the fatigue limit at 10^6 cycles (Fig. 9). The effect of overstressing the material by applying a single cycle with a very high peak stress and then cycling to failure at a much

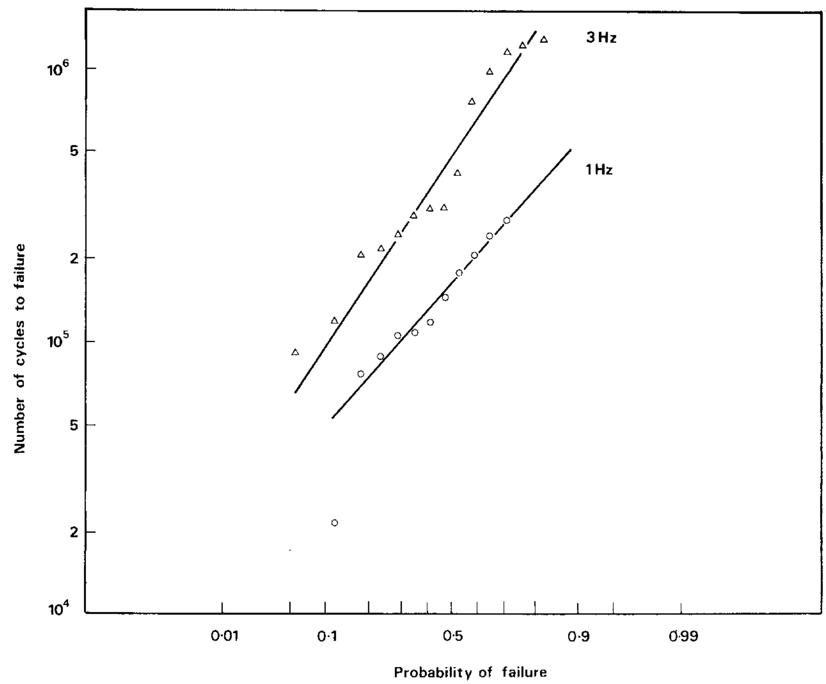

Figure 7 Effect of frequency on asbestos cement (mean maximum stress 21 MN m^{-2}).

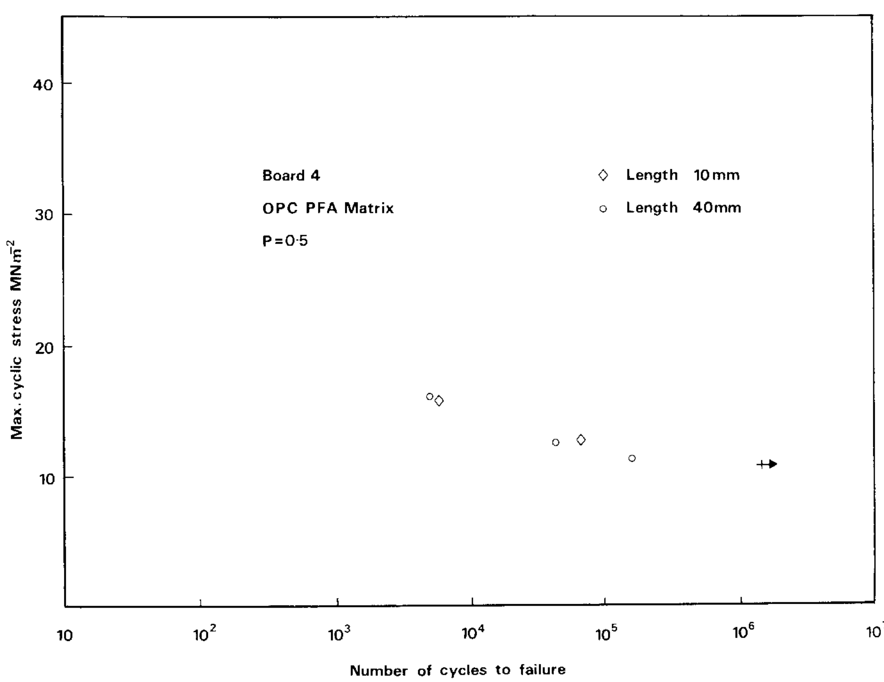

Figure 8 Effect of fibre length.

lower level is shown in Fig. 6.

The results of some MOR tests on specimens which did not fail during the fatigue tests are given in Table II. The first group, board 7, shows that the residual strength of specimens cycled with a peak stress approximately equal to that at the LOP had dropped to about two-thirds of the original value after 10^6 cycles. This is very reasonable considering the large amount of internal damage on a microscale these specimens (which had only a small probability of sustaining this number of cycles) must have undergone. The second group

TABLE II

Board	Max. cyclic stress ($MN\,m^{-2}$)	Median life (cycles)*	No. of cycles completed, N	Probability of failure by N cycles*	MOR after N cycles ($MN\,m^{-2}$)	Mean initial MOR ($MN\,m^{-2}$)	% of static strength remaining
Board 7	11.7	6.0×10^5	1.3×10^6	0.98	20.4	34.3	59
air stored	11.7	6.0×10^5	1.3×10^6	0.98	22.7	34.3	66
LOP =	13.5	2.5×10^5	7.8×10^6	0.82	19.8	34.3	58
$10.2\,MN\,m^{-2}$	13.5	2.5×10^5	7.8×10^6	0.82	25.0	34.3	73
	13.5	2.5×10^5	7.8×10^6	0.82	21.6	34.3	63
Board 1 water stored LOP = $13.2\,MN\,m^{-2}$	7.3	–	1.0×10^6	No failures in run of 16 specimens	42.4^+	42.0	100

* Taken from P–N line.

$^+$ Mean of six specimens.

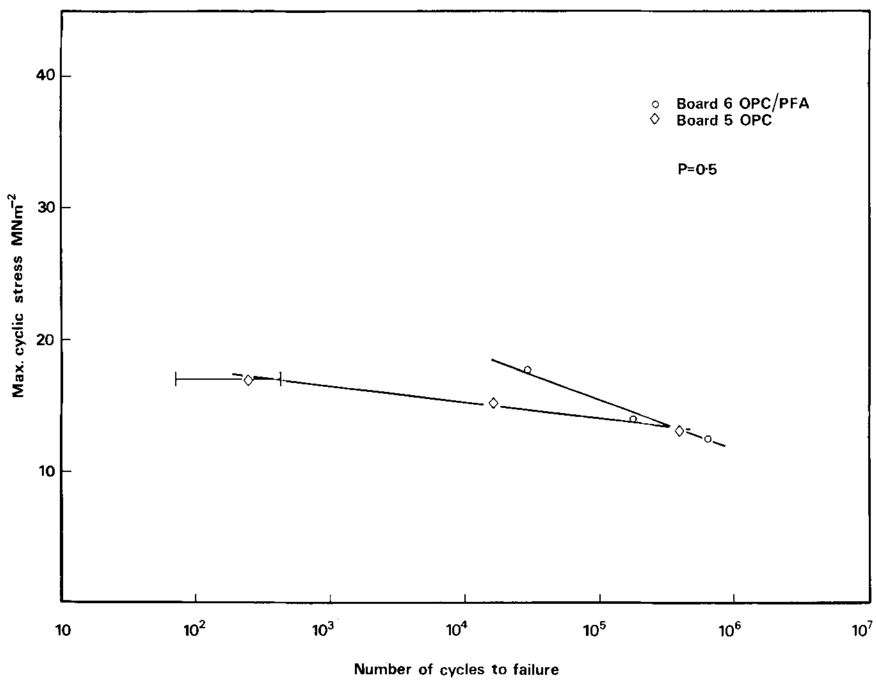

Figure 9 OPC and OPC + PFA, natural weathering, 1 year.

were subjected to a maximum cyclic stress about half that at the LOP and no specimens in the group of sixteen failed within 10^6 cycles. The mean MOR of these does not differ significantly from the initial value indicating that very little damage had occurred.

The mode of failure followed the conventional pattern for fatigue of materials in that the maximum deflection after the first few cycles remained constant during the major part of the test, i.e. up to about 90% of the total number of cycles to failure. There was then a rapid rise and one or more cracks became clearly visible on the tensile face perpendicular to the direction of stress. The specimen then failed completely by the propagation of a single crack.

The amount of fibre pull-out varied quite considerably being greater in the OPC/PFA boards at

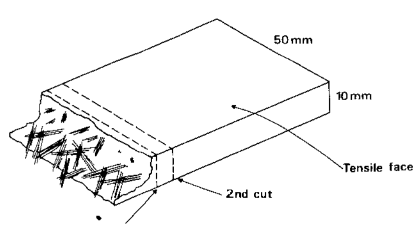

Figure 10 Cutting diagram for thick section to be photographed by transmitted light.

TABLE III

No. of cycles to failure ($\times 10^4$)	Total no. of strands visible	No. in compression region	No. in tensile region
4.4	99	68	31
7.3	105	73	32
3.7	141	90	51
6.8	108	71	37
7.3	97	62	35
17.0	96	67	29
	Mean 108	Mean 71	Mean 36
12.3	123	81	42
12.9	118	70	48
14.3	103	61	42
15.3	109	67	42
13.9	125	73	52
16.0	110	65	45
	Mean 115	Mean 70	Mean 45
Greater than	119	68	51
50×10^4	150	88	62
	117	70	47
	131	80	51
	129	78	51
	120	57	63
	Mean 128	Mean 74	Mean 54

early ages than in the older OPC boards. This is consistent with the static behaviour where the material tends to lose some of its ductility as the bond between the fibre and matrix increases with age.

Using a method developed by the author [8] it was possible to make an assessment of the quantity of "effective" reinforcement, i.e. that closely aligned to the direction of stress, in failed test coupons.

Forty-eight random specimens from the same board were tested in three groups of sixteen. Each was subjected to the same maximum cyclic load and the first, second, eighth, ninth, fifteenth and sixteenth specimens to fail in each of the three runs were chosen for examination. This gave three groups of six representing early, median and late failures. Sections of equal depth, approximately 7 mm, were cut parallel to the crack as indicated in Fig. 10 and photographed by transmitted light. The number of strands visible in the nominal tensile and compressive zones, i.e. the zones on either side of the major axis of symmetry are given in Table III and a photograph of a typical section is given in Fig. 11. It can be seen from Table III that in general there were more strands in the compression zone than in the tensile zone of the specimens. This asymmetry arose from inadequate control experience in operating the mechanized rig for manufacturing the specimen boards. It will be

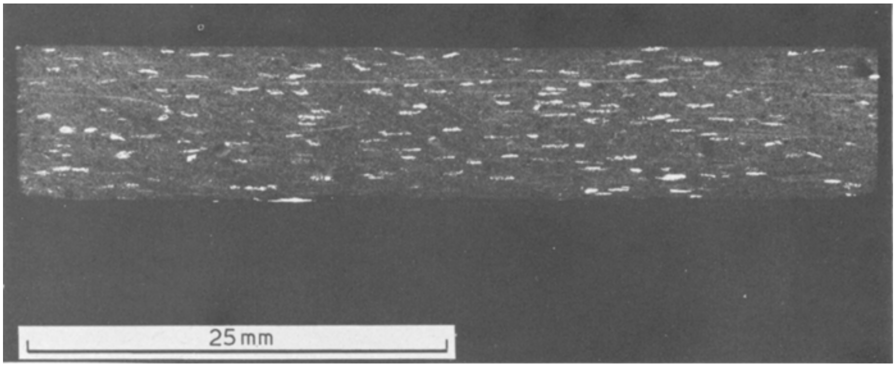

Figure 11 Typical section of GRC showing fibre bundles.

seen that coupons with a low lifetime were those which had a deficiency of reinforcement in the tensile region, i.e. the fatigue life for a given stress increases as the fibre volume fraction in the tensile zone increases.

5. Discussion and conclusions

It has been shown that the high cycle fatigue life of GRC composites is closely related to the stress at first crack and is, therefore, controlled by the properties of the matrix rather than the fibre since until the matrix has cracked the stress carried by the fibre is small. Above the LOP the fatigue life is reasonably well represented by a straight line projected back to the static ultimate strength. Fatigue at these levels will be governed by the properties of the reinforcement and its bond with the matrix, failure taking place by a combination of fibre pull-out and breakage.

It has not been possible in the present work to determine whether an endurance limit as such exists for the material. This would require testing to be extended up to at least 10^8 cycles which would necessitate the use of cycling rates beyond the capability of the present equipment. There are strong indications, however, that the slope of the S–N curve is reduced when the maximum stress is less than that at the LOP (Figs. 3 and 6). At such low stresses it was found that very few, if any, specimens failed by 10^6 cycles which suggests a very high median life – in the order of 10^{10} cycles – especially since the scatter of results was observed to increase as the stress was reduced.

The results obtained for GRC are consistent with those that have been reported for the repeated flexure of steel fibre reinforced concrete [9] where cycling at 90% of the first-crack strength gave a fatigue life of 2×10^6 cycles with 2 to 3% of fibre by volume.

Acknowledgements

The authors wish to thank Dr A. J. Majumdar for the help and encouragement he has given throughout this work and Mr A. C. Irwin who assisted with much of the testing. The work described has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director, and of H.M.S.O., holder of Crown Copyright.

References

1. B. R. STEELE, Glass Fibre Reinforced Cement. Proceedings of International Building Exhibition Conference, London (1971).
2. F. J. GRIMER and M. A. ALI, *Mag. Concrete Res.* 21(66) (1969) 23.
3. H. G. ALLEN, *J. Comp. Mats.* 5 (1971) 194.
4. M. A. ALI and F. J. GRIMER, *J. Mater. Sci.* 4 (1969) 389.
5. British Standard 3518: Part 5 (1966).
6. G. J. HAHN and S. S. SHAPIRO, "Statistical models in engineering" (John Wiley, New York, 1968) Ch. 8.
7. J. W. GALLOWAY and K. D. RAITHBY, Transport and Road Research Laboratory TRRL Report LR 547 (1973).
8. A. P. HIBBERT, *J. Mater. Sci.* 3 (1974) 512.
9. A.C.I. Committee 544, "State-of-the-art report on Fiber Reinforced Concrete", 70 (1973) 729.

Received 20 January and accepted 28 April 1975.