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by

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A COMPRESSIVE TEST SPECIMEN FOR UNIDIRECTIONAL
CARBON FIBRE REINFORCED PLASTICS

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SUMMARY

A compressive test specimen has been developed for unidirectional carbon fibre reinforced plastics which enables the ultimate compressive strength to be determined. Failure occurs remote from the specimen ends and tests show good repeatability. Results are compared with theory and reasons for the differences are discussed.

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1 INTRODUCTION

To enable design studies using carbon fibre reinforced plastics (CFRP) to be carried out with confidence it is necessary to determine material properties. In compression testing the cylindrical section slugs used for isotropic materials, particularly metals, are quite unacceptable for unidirectional CFRP which is highly anisotropic. Transverse loads set up in the ends of a test specimen under a compressive load are small compared with the ultimate transverse strengths of metals, but may well exceed the ultimate transverse strength (i.e. normal to the fibre direction) of unidirectional CFRP where transverse properties are poor and depend largely on the properties of the plastic matrix and the fibre-plastic interface. For this reason, failure is likely to occur at the ends of such a unidirectional CFRP specimen before the true ultimate compressive strength has been realised.

This report describes the development of a test specimen which allows the measurement of ultimate compressive strength and modulus of unidirectional CFRP, loaded in the fibre direction, independent of any end effects. Test procedures are also described, together with results obtained from a trial series of tests. The results are compared with theory and possible reasons for rather poor agreement are discussed.

2 DEVELOPMENT OF THE TEST SPECIMEN

Initial compression tests (series 1) were carried out on unidirectional CFRP specimens of rectangular cross-section, 12.7 mm × 6.3 mm (0.5 in × 0.25 in), and 25.4 mm (1 in) long, with the end faces machined flat and normal to the fibre direction. Testing was carried out between the fixed compression plattens of a 50 ton Avery Universal testing machine at constant strain rate giving failure in about 30 s. Failures consistently occurred at the ends of the specimens with a complete breakdown of the matrix, the fibres splaying out to give a brush-like appearance.

In an attempt to prevent this mode of failure, a further set of specimens (series 2) was made, of the same size and shape, with the ends cast in an epoxy resin which provided a degree of lateral support. The specimens were prepared and tested as before. Although failure occurred at a higher stress, indicating that some lateral support had been achieved, it was still due to failure in the specimen ends which were of the same brush-like appearance as for series 1. A photograph of typical failures in these specimens is shown in Fig.1.

Two important factors emerged which are obviously contributory to the premature failure of the test specimens. Firstly, the sudden change in cross-sectional area from the compression plattens to the test specimen sets up a complex stress field which can lead to lateral loading of the specimen ends. Secondly, machining the specimen ends tends to leave a roughened surface in which many of the fibres protrude from the resin surface. Under a compressive load, these fibres are preferentially loaded and, having little lateral support, buckle at low stress levels. The combined effect of these two factors is to induce lateral loads in the surrounding resin, giving rise to an early breakdown in the resin-fibre interface and premature failure of the specimen. Evidence in support of this mode of failure is clearly given from the brush-like appearance of the ends of failed specimens.

It was clear from the results so far that a substantial degree of lateral support at the ends of a specimen would be necessary to prevent unrepresentative failure of the kind previously described. With this end in view, a special end fitting was designed, largely on an empirical basis. This was made from mild steel, chosen for its strength, Young's modulus (compatible with CFRP) and ease of machining.

A piece of 12.7 mm (0.5 in) diameter rod was cut to a length of 25.4 mm (1 in). Into one end a hole 5.5 mm (0.219 in) diameter was drilled to a depth of about 12.7 mm (0.5 in) and the outer surface tapered to give a feather edge at the mouth of the hole. A length of 6.3 mm (0.25 in) square section unidirectional CFRP was machined to a diameter of 5.5 mm (0.219 in), cut to 50.8 mm (2 in) long and the ends coned to match the tip of the drill used on the end fitting. A thin smear of epoxy adhesive was applied to each end of the CFRP test piece and an end fitting pressed onto each end. After the adhesive had cured, the steel ends were machined flat and normal to the test piece axis. A diagram of the test specimen (series 3), showing dimensions of the test piece and end fittings, is shown in Fig.2.

Compression testing was carried out in the same manner as for the previous specimens. The specimens failed at a considerably higher stress than the first series, and failure occurred not at the end of the test piece but at the junction with the further edge of the end fitting. Study of the failure showed it to be of a different mode from the series 1 failures with no sign of the brush-like failure in the ends. A photograph of some failed specimens is shown in Fig.3. It appeared, therefore, that this end fitting provided adequate

lateral support, but there was evidence that the feather edge at the mouth of hole suffered distortion during some of the tests. Furthermore failures still generally occurred near the end fitting, although the failure mode was clearly much more representative of true compression than was that of the earlier specimens of series 1 and 2.

Two further modifications were therefore made to the specimen design. Firstly, the end fittings were tapered not to a feather edge but to a wall thickness of 1.27 mm (0.05 in). This not only prevented distortion of the end fitting but also made the machining process simpler. Secondly, the centre section of the test piece was waisted to about 80% of the nominal diameter with the aim of precipitating failure in this region. Tests on specimens of this design (series 4) showed that the degree of waisting was sufficient to ensure that, in nearly every case, failure occurred at the waisted section remote from the end fittings. The only exceptions occurred in specimens where the interlaminar shear strength was extremely low, causing early breakdown of the resin-fibre interface.

3 THE STANDARD SPECIMENS

Three standard specimen sizes have been adopted, based on the successful design of the series 4 specimens previously described, for use with unidirectional CFRP bars moulded to 12.7 mm (0.5 in), 9.5 mm (0.375 in) and 6.3 mm (0.25 in) square cross-section. This allows compression tests to be carried out on a wide range of available mouldings and will enable the effect of size on ultimate compressive strength to be determined. The ratio of length to waisted diameter has been kept constant, but a waisted gauge length of 12.7 mm (0.5 in) has been used for all three sizes to allow for the use of the same strain measuring equipment. The dimensions of the test specimens are given in Fig.4 and a photograph of the three sizes of specimen prepared for testing is included as Fig.5.

4 TRIAL TESTS

Although the full range of compression testing of unidirectional CFRP has yet to be covered, a trial series of tests was carried out to confirm the specimen design and to obtain a preliminary set of design data. These tests were in two parts: firstly, measurement of ultimate compressive strength as a function of fibre volume fraction; and secondly measurement of ultimate compressive strength for various carbon fibre batches.

4.1 Compressive strength as a function of the volume fraction

These tests were carried out using the series 3 specimen design before the series 4 specimen had been fully developed. Subsequent tests (see section 4.2) have shown that the ultimate failing stress, for similar CFRP mouldings, is unaffected by a change from series 3 to series 4 specimen shape: the effect of waisting is simply to ensure that failure occurs in a region away from the specimen ends.

Five unidirectional CFRP mouldings were made, covering a range of fibre volume fractions from 0.3 to 0.56, from metre-length Type I fibre produced at A.E.R.E., Harwell and surface treated at R.A.E., and a hot setting epoxy resin system*. The standard flow control moulding technique was used giving a finished moulding size of 152.5 mm (6 in) length and 6.35 mm (0.25 in) square cross-section. Each specimen was prepared as previously described (section 2) and gave either two or three compression test specimens. Details of the test specimens including dimensions and fibre volume fractions are given in Table 1.

The compression test was carried out on an Avery Universal testing machine set to the 5 ton range. Each specimen was carefully positioned between the compression test plattens and the load applied at a constant strain rate, causing failure in about 20 s. No strain measurements were made. In every case failure was sudden and catastrophic and was accompanied by an immediate drop in the applied load. The results of the tests are given in Table 2, and a graph of ultimate compressive strength against fibre volume fraction is shown in Fig.6.

As expected, the results show that the compressive strength increases with increasing fibre volume fraction and is approximately inversely proportional to $1 - v_f$, where v_f is the fibre volume fraction. This relationship is discussed more fully in section 5.

4.2 Compression strength for various fibre batches

In order to obtain preliminary data on batch-to-batch variations, compression tests were carried out on unidirectional CFRP made from several

* Shell 828 resin, MNA and benzyl dimethylamide [~]100/85/1 parts by weight cured at 100°C for 1 hour and post-cured at 120°C for 24 hours.

different batches of metre-length Type I fibre surface treated at R.A.E. For this series of tests the largest of the standard specimens (series 4) was used and a constant fibre volume fraction of 0.5 chosen, being typical of the level of fibre reinforcement generally used. The specimens were made and tested in the same way as previously described, and the failing loads and stresses are given in Table 3. The results confirm the ultimate compressive strengths found from the series 3 trial tests and show that, in general, batch-to-batch variations fall within the scatter limits obtained from tests on a single batch.

5 THEORY

Although the cause of compression failure in unidirectional CFRP is uncertain, it has been suggested by Dow¹ that fibre reinforced plastics fail due to fibre buckling within the plastic matrix. He has proposed a two-dimensional model in which parallel, high modulus, high strength fibres are supported against buckling by a matrix of low strength and modulus. When load is applied to the fibres two simple buckling modes are possible and may be defined as in-phase and out-of-phase sinusoidal buckling. The in-plane mode occurs when all fibres buckle with the same wavelength and adjacent fibres are in phase (Fig.8a). The out-of-phase mode occurs when adjacent fibres are out of phase by π , although buckling with the same wavelength (Fig.8b). Due to the effect each mode has on the matrix, they are generally referred to as the 'shear' and 'extension' modes respectively.

An analysis of the two buckling modes yields the critical composite compressive stress, σ_c , at which buckling is unstable and leads to overall composite failure.

For the shear mode the critical stress is:

$$\sigma_c = \frac{G_m}{(1 - v_f)}$$

where G_m is matrix shear modulus

and v_f is fibre volume fraction.

In the case of the extension mode, the critical stress is:

$$\sigma_c = 2 v_f \left(\frac{v_f E_f E_m}{3 (1 - v_f)} \right)^{\frac{1}{2}}$$

where E_f is fibre Young's modulus

and E_m is matrix Young's modulus.

For carbon fibres, where Young's modulus is large, the shear mode predominates over the useful range of fibre volume fractions (i.e. $v_f > 0.15$). Substituting realistic numbers for the elastic constants, the curve of ultimate compressive strength as a function of fibre volume fraction is obtained and is shown, for Type 1 composites, in Fig.9. Also plotted is the curve obtained from the tests described in section 4.1.

6 DISCUSSION

It will be seen from Fig.9 that the theory predicts strengths several times larger than the strengths obtained from experimental tests. Several reasons for such large differences suggest themselves.

(a) The idealised two-dimensional model assumes all the matrix material is used in resisting buckling. However, in the real three-dimensional case fibres are of circular cross-section and spaced apart in the third dimension. Planes of resin occupying the spaces between fibres (i.e. spaces between fibres in the third dimension) are only indirectly sheared by fibre buckling. Resin in these regions will therefore be relatively ineffective in resisting fibre buckling. In tests on boron-epoxy unidirectional composites, for example, Lager and June² have shown that, for a square array of fibres, a reduction factor of 0.63 must be applied to the theoretical expression for ultimate strength in order to allow for this effect. In the case of carbon fibre composites, where the fibre arrangement is random, it is likely that a more drastic reduction factor should be used.

(b) The fibre distribution over the cross-section of a unidirectional CFRP specimen is by no means regular or uniform, particularly at the lower fibre volume fractions. At some places on the cross-section, therefore, the local volume fractions will be less than the mean, resulting in compressive strengths less than predicted by a theory based on mean fibre volume fraction. Experimental evidence tends to confirm this argument; at a volume fraction of 0.3 the ratio between theoretical and experimental strengths is 5.5, but at a volume fraction of 0.55 the ratio is reduced to 3.5.

(c) The assumption that fibres are straight and parallel is by no means true in real CFRP specimens. Any misalignment or kinks in the fibres will reduce the fibre buckling stress and, in turn, reduce the composite ultimate strength.

(d) Theory assumes a perfect bond between fibre and matrix and this is not so in the practical case. Although this will have very little effect on the

strength predicted by the shear mode failure, its effect on the extension mode may be considerable. This would result in an increase in the fibre volume fraction at which the critical mode of failure changes from the extension mode to the shear mode. Evidence of this effect was apparent in early compressive tests where a low interlaminar shear strength, a measure of the fibre-resin bond, was associated with low ultimate compressive strengths, particularly at the lower fibre volume fractions.

These effects all tend to reduce the ultimate compressive strength of unidirectional CFRP below the theoretical predictions, but by amounts which it would be difficult to quantify. However, the shapes of the theoretical and experimental curves for compressive strength against fibre volume fraction are similar and this lends some support to the suggested modes of failure.

The experimental values are satisfactorily reproducible and, being uninfluenced by any end effects or stress concentration effects, are believed to be representative of the true ultimate compressive strength of unidirectional CFRP for the materials used.

7 CONCLUSIONS

The compressive test specimen developed for unidirectional carbon fibre reinforced plastic enables the ultimate compressive strength to be measured with confidence. Although considerable care is required in the preparation of the specimen no specialised test equipment or procedures are required. Test results have shown good reproducibility and because failure is uninfluenced by end effects the measured failing stresses are believed to be representative of the compressive strength of unidirectional CFRP.

The variation of failing stress with fibre volume fraction is of the general form expected from theoretical considerations and the magnitude of the failing stress is of the order of 25% of that predicted from a simplified theoretical analysis in which a number of drastic assumptions were made.

Table 1

SPECIMEN DATA

Test specimen	Fibre volume fraction	Specimen diameter	
		mm	in
1A	0.47	5.69	0.224
1B	0.47	5.51	0.217
2A	0.40	5.38	0.212
2B	0.40	5.51	0.217
3A	0.31	5.41	0.213
3B	0.31	5.44	0.214
3C	0.31	5.51	0.217
4A	0.52	5.54	0.218
4B	0.52	5.54	0.218
5A	0.56	5.51	0.217
5B	0.56	5.49	0.216

Table 2

ULTIMATE COMPRESSIVE STRENGTH FOR
 VARIOUS FIBRE VOLUME FRACTIONS

	Failing stress		Mean failing stress	
	MN/m ²	lbf/in ²	MN/m ²	lbf/in ²
1A	482.6	70 000	551.7	80 020
1B	620.8	90 040		
2A	293.0	42 500	376.8	54 650
2B	460.6	66 800		
3A	273.7	39 700	279.9	40 600
3B	304.7	44 200		
3C	263.4	38 200		
4A	628.8	91 200	612.9	88 900
4B	597.0	86 600		
5A	723.9	105 000	727.1	105 450
5B	730.2	105 900		

Table 3
ULTIMATE COMPRESSIVE STRENGTH FOR VARIOUS
FIBRE BATCHES

(Fibre volume fraction 0.5)

Specimen No.	Fibre batch	Failing stress		Mean failing stress	
		MN/m ²	lbf/in ²	MN/m ²	lbf/in ²
1A	Harwell 14	513	74 500	522	75 833
1B		503	73 000		
1C		551	80 000		
2A	Courtaulds 3	566	82 200	575	83 533
2B		582	84 400		
2C		579	84 000		
3A	Courtaulds 5	593	86 000	593	86 000
3B		593	86 000		
4A	Courtaulds 7	510	74 000	539	78 250
4B		569	82 500		

REFERENCES

<u>No.</u>	<u>Author(s)</u>	<u>Title, etc.</u>
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2	J.R. Lager R.R. June	Compressive strength of boron-epoxy composites. Journal of Composite Materials - July 1969

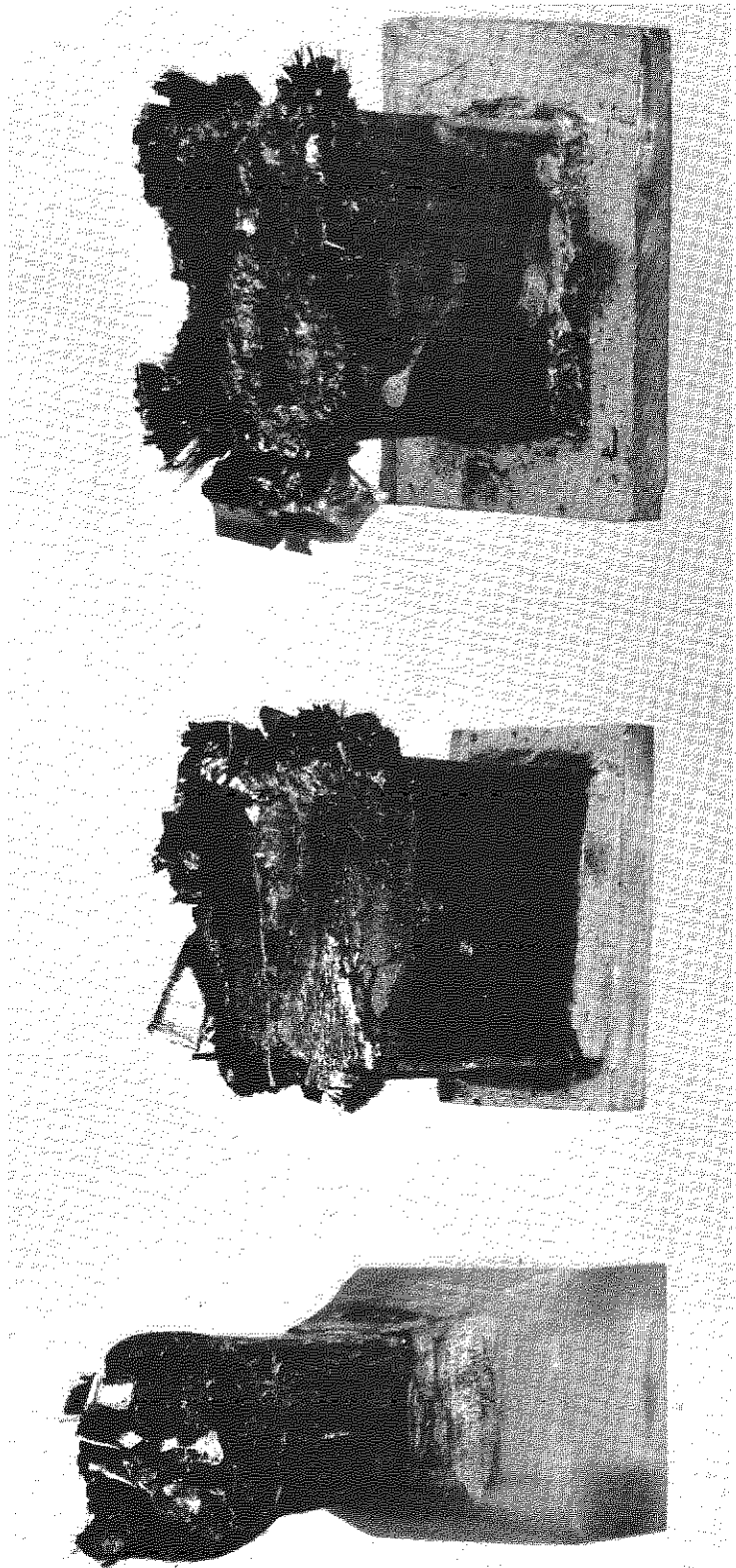


Fig.1. Typical failures in series 2 specimens

08 .14 .3 .42 .52 .63 .74 .85 .96 1.07 1.18 1.29 1.40 1.51 1.62 1.73 1.84

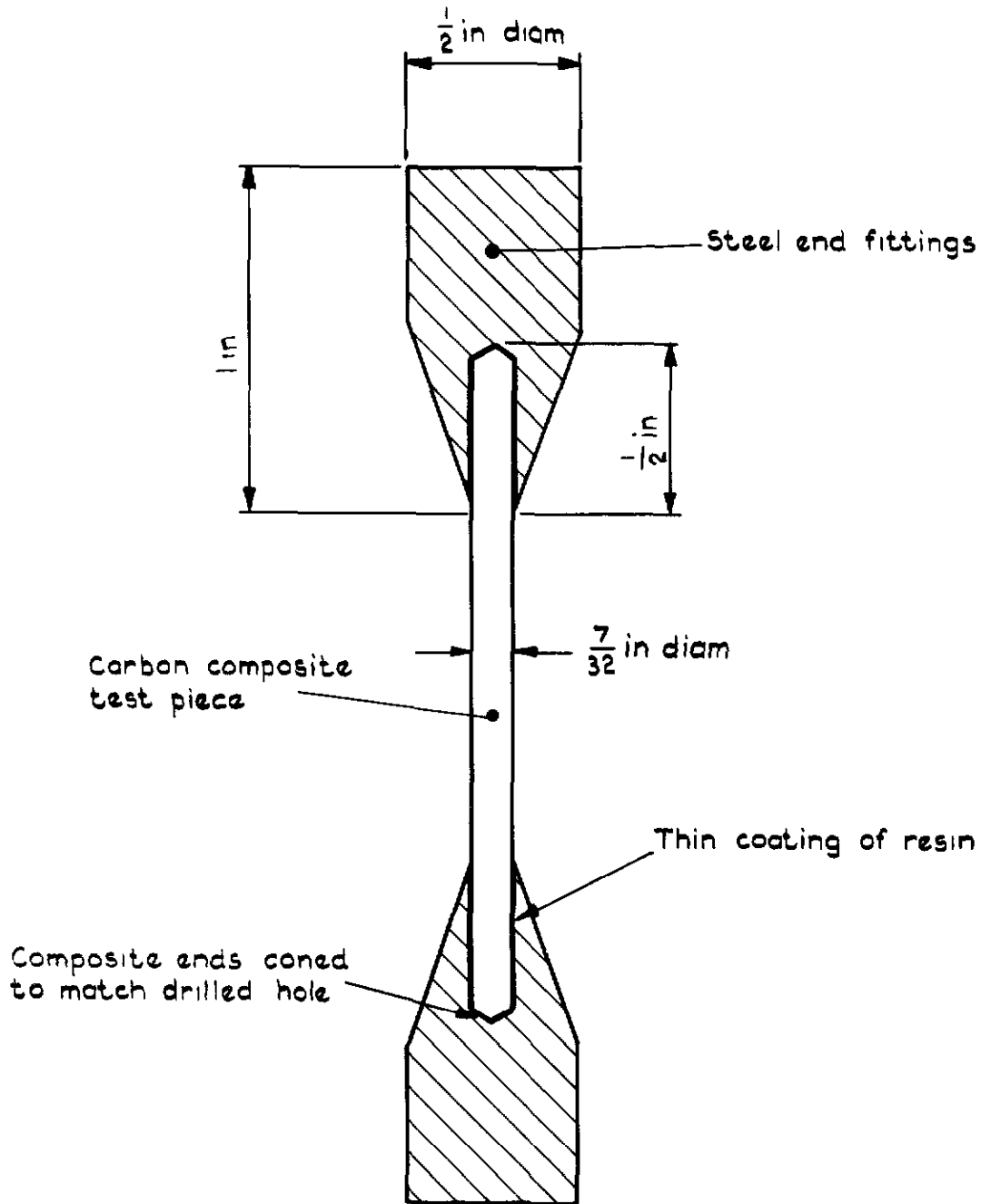


Fig 2 Series 3 test specimen

08 14 3 42 52 68 1 1.2 1.6 1.8

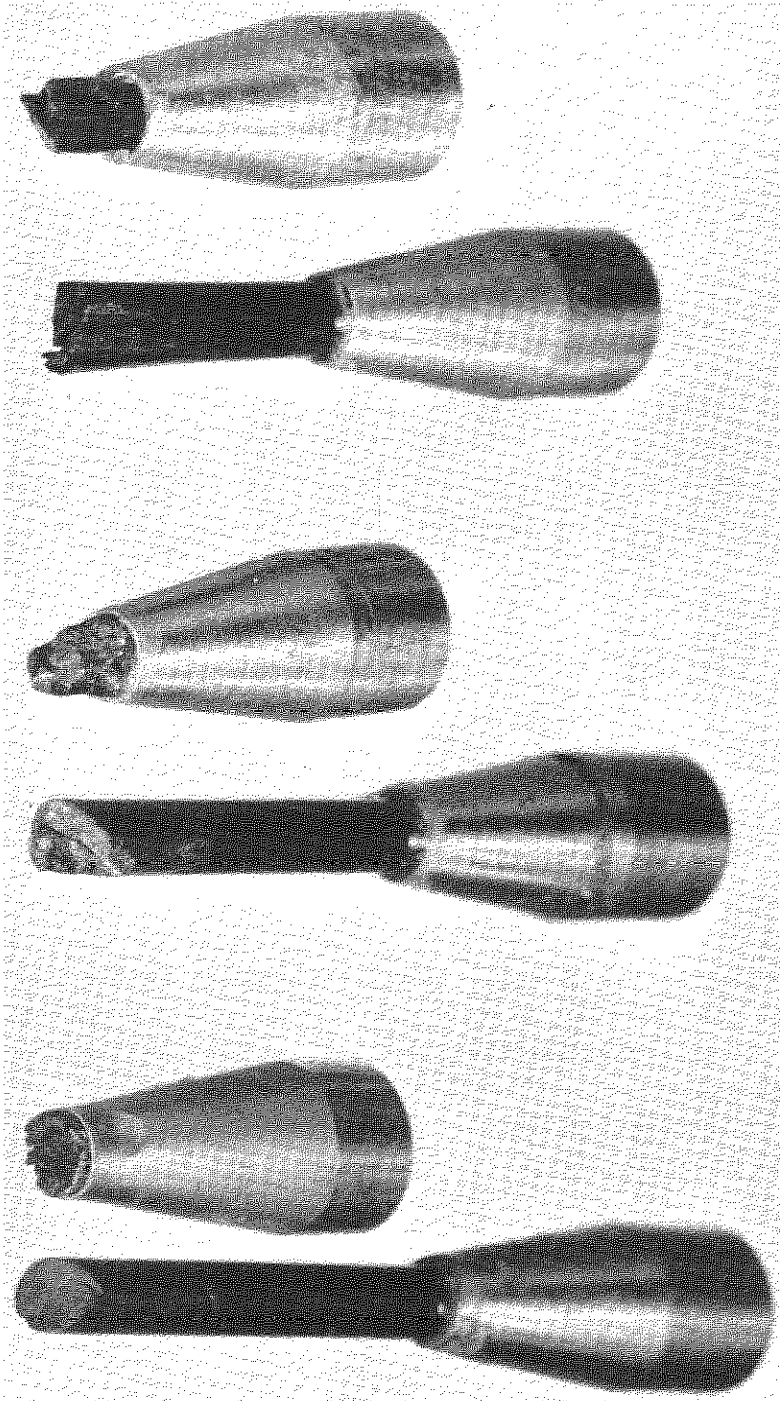
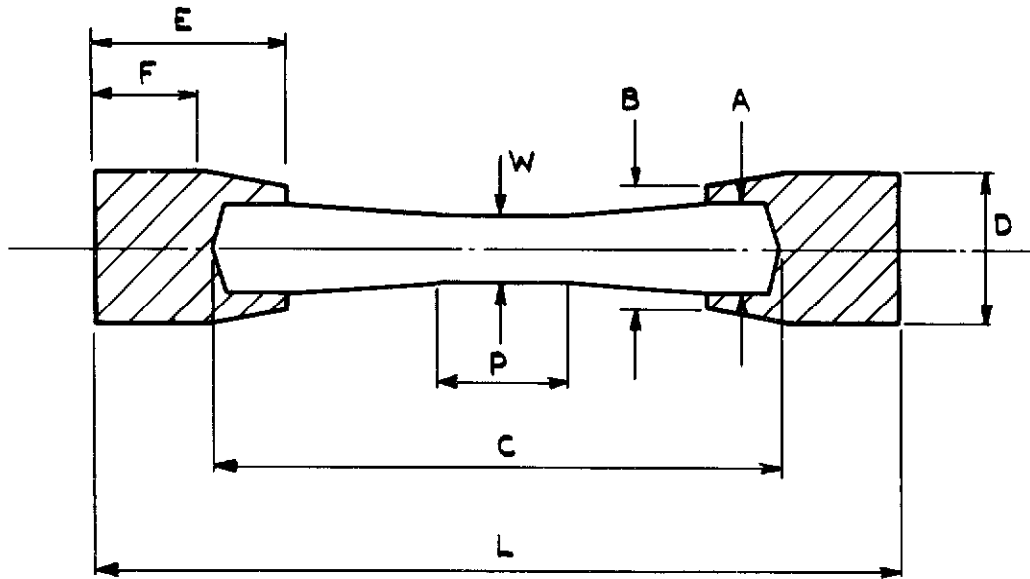


Fig.3. Typical failures in series 3 specimens



	A		B		C		D		E		F		L		P		W	
	diam	diam	diam	diam	nominal	diam	diam	diam	diam	diam	diam	diam	diam	diam	diam	diam	diam	
	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Size A	.43	10.9	.5	12.7	3.0	76.2	.75	19	1.0	25	.6	15	4.2	107	.5	12.7	.33	8.4
Size B	.37	9.4	.44	11.2	2.25	57.2	.75	19	1.0	25	.6	15	3.5	89	.5	12.7	.28	7.1
Size C	.24	6.1	.31	7.9	1.5	38.1	.5	12.7	1.0	25	.6	15	2.7	69	.5	12.7	.18	4.6

Fig4 Details of series 4 (standard) specimens

08 14 3 42' 52 68 9 1.2 1.6 1.8

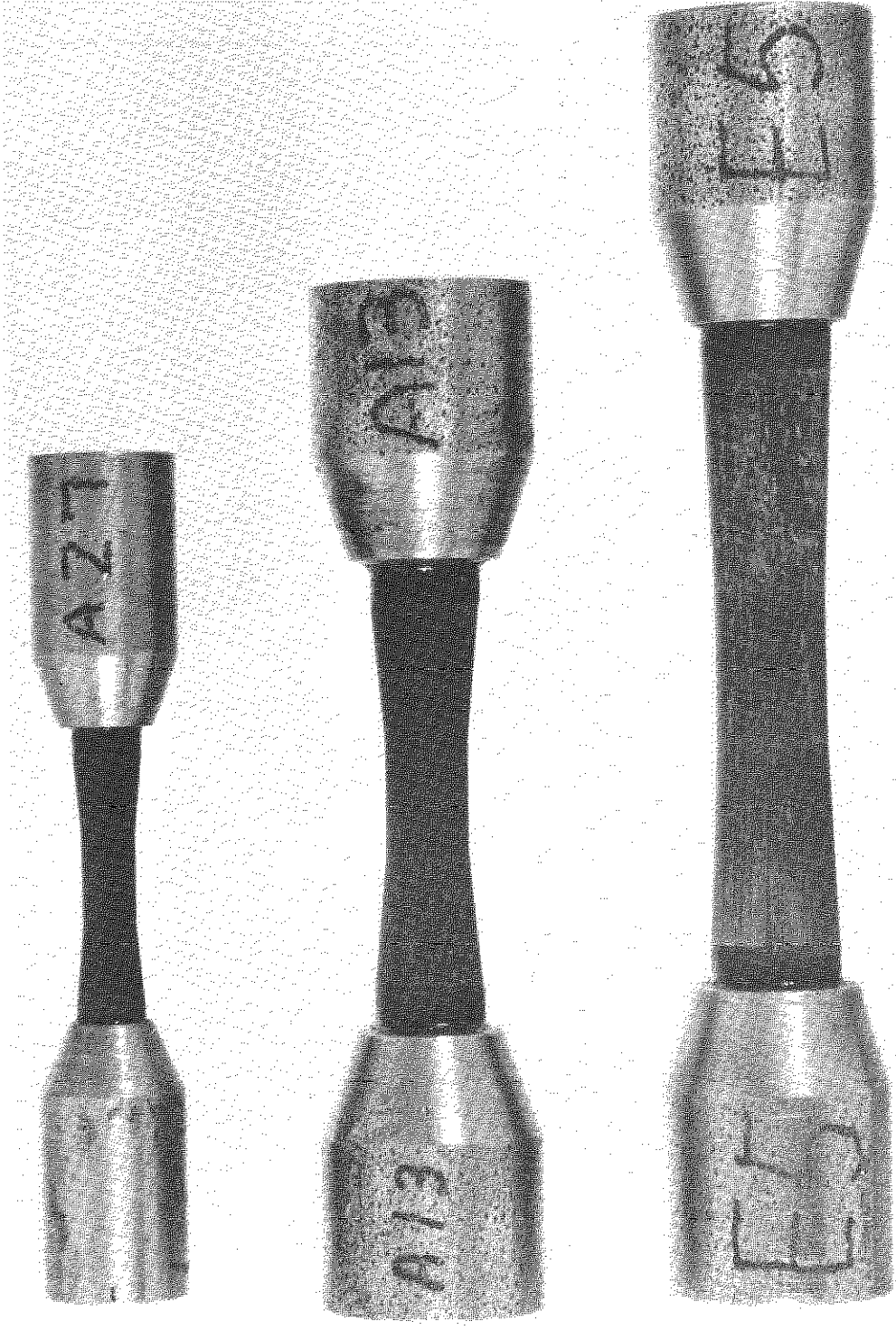


Fig.5. The three series 4 specimens prepared for testing

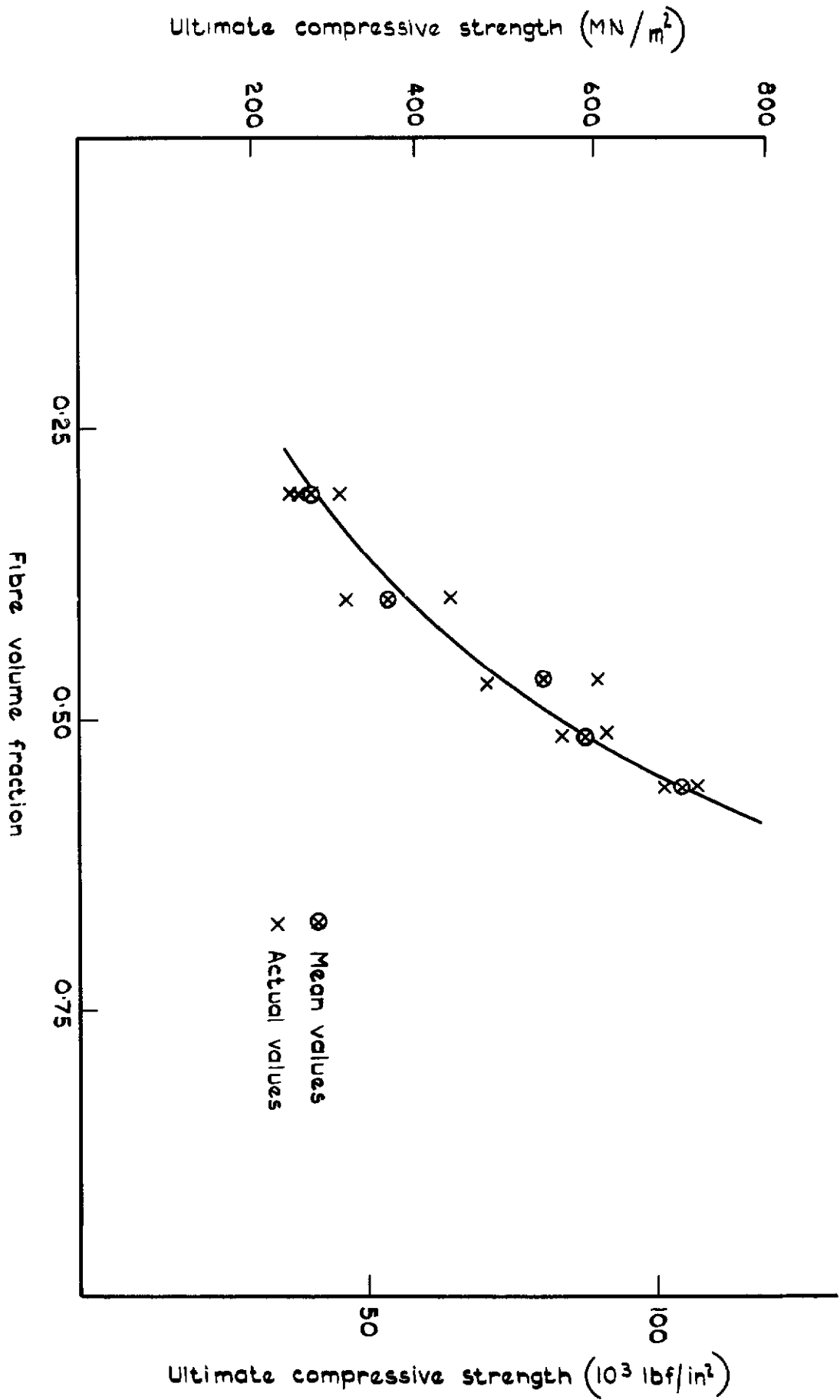


Fig 6 Ultimate compressive strength as a function of fibre volume fraction

08 14 3 42 52 68 84 100 116 132 148 164 180

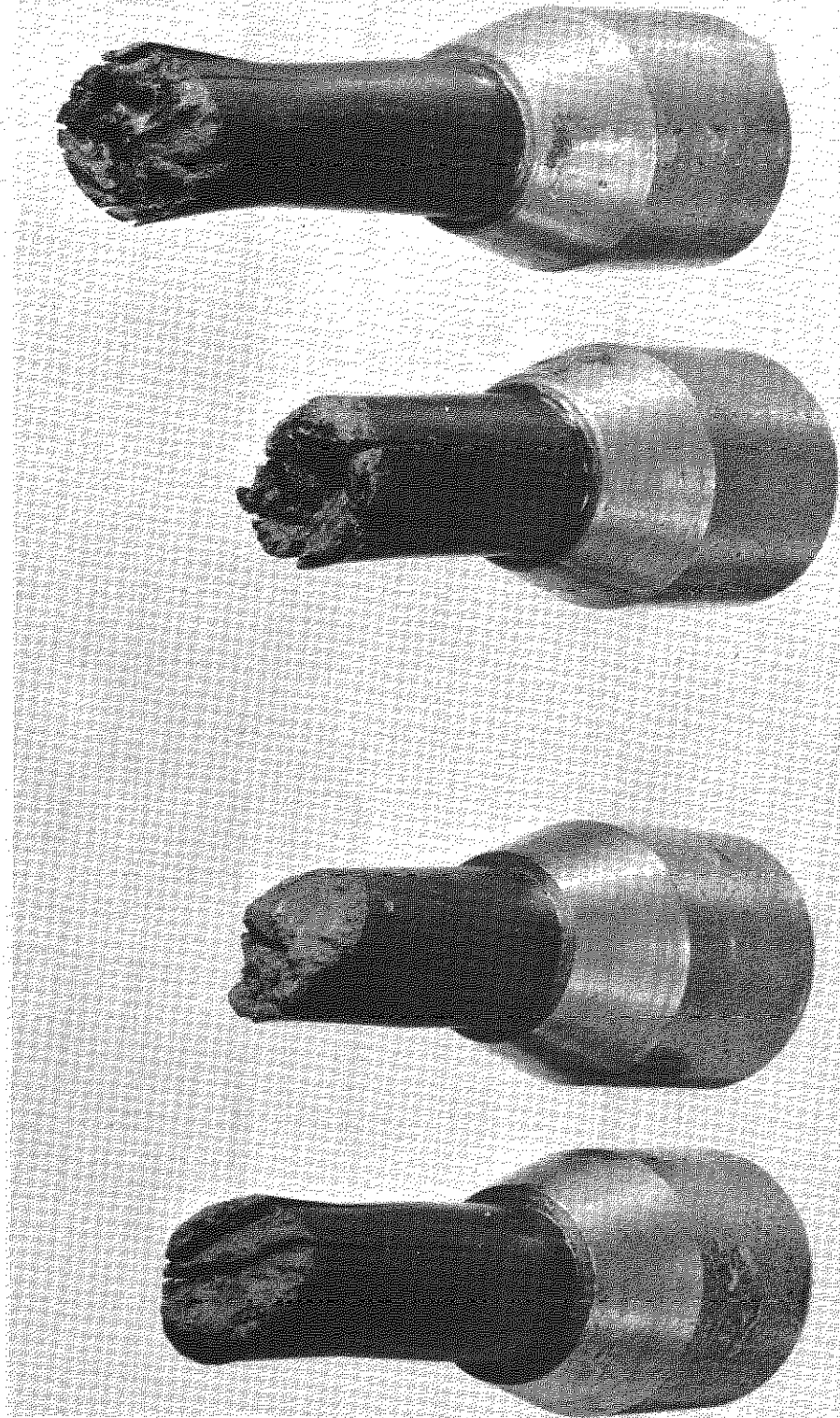
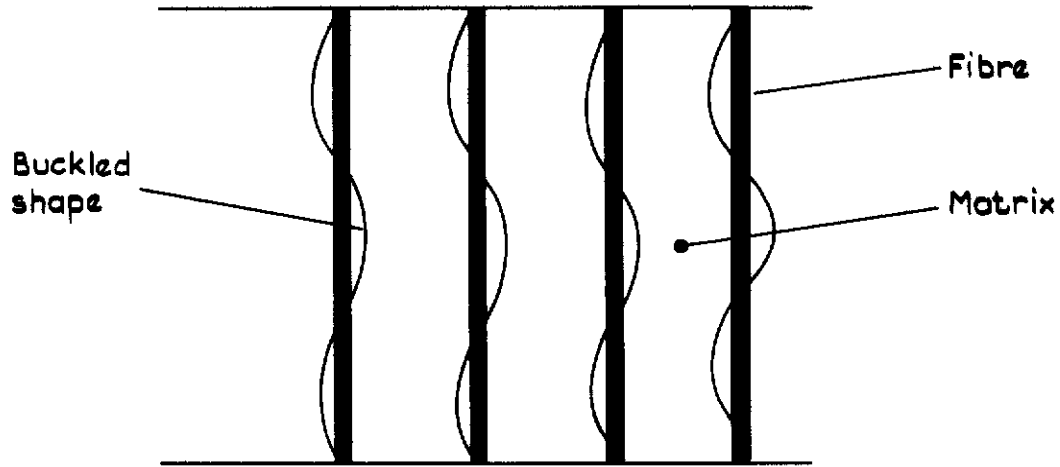
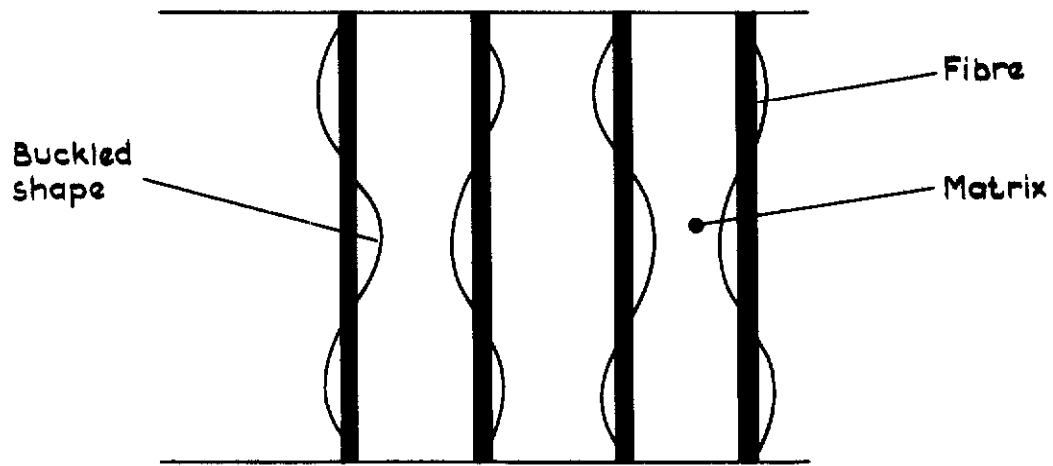


Fig.7. Typical failures in series 4 specimens



a Shear mode (in - phase)



b Extension mode (out - of - phase)

Fig.8a&b The two modes of fibre buckling

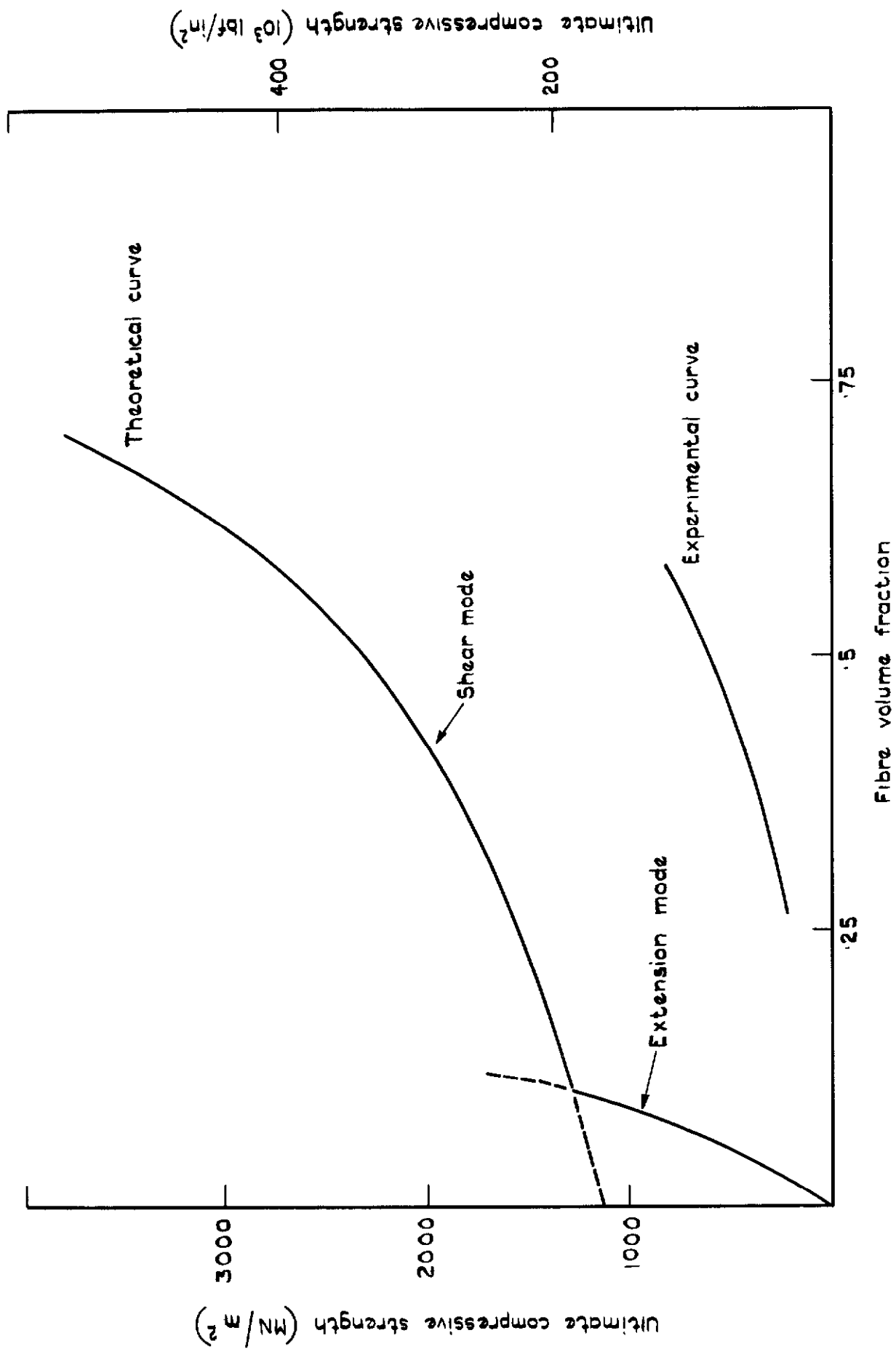


Fig 9 Ultimate compressive strength as a function of fibre volume fraction

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