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SUMMARY

The design and evaluation of flat specimens for the determination of the compressive strength and modulus of unidirectional carbon fibre reinforced plastics laminated from resin pre-impregnated sheets are described. Tests indicate that the values obtained reflect reliably the true properties of the materials.

Departmental Reference: Structures YSE/B/0411

CONTENTS

1 INTRODUCTION

The acquisition of accurate material properties data is a fundamental precursor to the design of structural components in a new material. Standard test specimen configurations and techniques used for isotropic materials are not however applicable to composites such as unidirectional carbon fibre reinforced plastic (CFRP) which possess a high degree of anisotropy and are linearly elastic to failure when loaded in the direction of the fibres.

In the determination of the ultimate strength of most conventional structural materials, any bending stresses induced in an axially loaded specimen by initial curvature or test machine misalignment are relieved by local plasticity causing negligible reduction in the measured ultimate strength. However, in CFRP, any similar stresses tend to cause premature failure due to the lack of ductility of the fibres. In order to ensure failure in the test section away from end effects or fittings, it is necessary to waist specimens to a region of uniform stress. The very high ratio of compressive strength in the direction of the fibres to shear strength in planes parallel to the fibres, necessitates careful design of the waisting profile, governed by load diffusion consideration, so as to reduce these stresses to below the ultimate shear strength.

A compressive test specimen for the determination of the strength of unidirectional CFRP has been described by Ewins[1]. This specimen is of circular section and is moulded by the standard flow control technique[2]. With the commercial availability of CFRP in the form of partially cured resin preimpregnated sheets came the necessity to ascertain the materials data for laminated unidirectional CFRP boards. This Report describes the design and evaluation of flat specimens cut from such boards for the determination of the compressive strength and stiffness in the direction of the fibres. The properties determined are thus typical of those attained in CFRP components manufactured by similar techniques. Specimen preparation is simple and consists merely of waisting in one plane and the attachment of simple expendable end fittings. This exercise is part of a programme of work for the evaluation of the longitudinal and transverse properties of unidirectional CFRP which is summarised in an earlier Report[3].

2 TEST SPECIMEN DESIGN

In addition to the design requirements related to load transfer, load diffusion, etc., it is desirable that the specimen should be of the same thickness as comparable specimens for the measurement of the longitudinal and transverse mechanical properties so that all specimens can be prepared from the same board. The thickness requirements for tensile and compressive specimens to some extent conflict and a compromise thickness of 2 mm was chosen.. This thickness was not always sufficient to provide overall stability when a parallel waisted section was incorporated for the measurement of composite stiffness. However, since unidirectional CFRP is approximately linearly elastic to failure under longitudinal compression, the Young's modulus need only, in general, be determined at relatively low stress values. Specimen design was therefore concentrated on the ultimate strength case, an unwaisted version of this specimen being used for the modulus determination.

The specimens were chosen to have sufficient width (10 mm) to provide a representative cross section of the material while remaining narrow enough for in-plane stresses arising from misalignment in the test machine to be negligible.

2.1 Ultimate compressive strength

When a material is compressed uniaxially transverse stresses are, in general, imposed near the ends due to local restraints. In isotropic materials these transverse stresses are unlikely to initiate failure but in CFRP, where the anisotropy may be such that the strength of the composite in the direction of the fibres (longitudinal) may be many times the strength in directions perpendicular to the fibres (transverse), transverse stresses may well precipitate failure before the specimen fails in compression. In addition, if the specimen is loaded directly between platens, contact imperfections between specimen and platen will induce local stress concentrations. In ductile materials these concentrations will be relieved by plastic flow, but CFRP being elastic to failure, will fail prematurely in this locality. Thus transverse stresses and local stress concentrations are both likely to contribute to premature failure at unreinforced ends which frequently has the brushed appearance illustrated in Fig.1. End fittings are thus needed to restrain the composite transversely; these are bonded to the specimen so that some load may be transferred via shear in the side faces. End fittings also contribute to the elastic stability of the specimens and facilitate accurate alignment in the test machine.

2.1.1 Specimen profile

To ensure failure of the composite away from the end fittings it is necessary to reduce the cross sectional area of the specimen in the unrestrained region. In order to minimise both the length of the reduced cross section to avoid buckling and also the effect of any test machine misalignment, the specimen was waisted in its thickness. The general configuration of a waisted test specimen, of uniform breadth, with reinforced ends is shown in Fig.2. Over the waisted length, the applied load must be transferred across the specimen thickness by shear and consequently the maximum rate of waisting is governed by the rate at which load in the X direction may be transferred in the Y direction in this manner, the limit being imposed either by the shear diffusion rate or by the ultimate shear strength τ'. In the present case it is the shear strength of the CFRP which is the governing factor and the equation derived for the limiting profile[3] is

$$y = \frac{d}{2} \exp \left| \frac{\tau'}{\sigma'} \frac{2x}{d} \right|$$

where d is the minimum thickness at the centre of the waisted section, $2y$ is the specimen thickness at a distance x from the centre and σ' is the ultimate compressive strength. If an unwaisted specimen were used, the stress concentration at the end fitting would always initiate failure; the degree of waisting must be sufficient to prevent this and preliminary experiments with different waistings led to a factor of 1.5 (i.e. basic thickness:waisted thickness = 3:2) being adopted. If the ratio of shear strength to compressive strength for CFRP is taken typically to be less than 1:30, then the waisted length ℓ is given by

$$\ell = 17.5d .$$

As discussed earlier, the basic specimen thickness was chosen to be 2 mm, giving a waisted thickness d of 1.35 mm; hence from equation (2) $\ell = 16.5$ mm. It was obviously not feasible in practice to obtain an exponential specimen profile and a close approximation was obtained using a 125 mm radius grinding wheel giving a length ℓ of 18 mm for a thickness d of 1.35 mm.

To determine the likelihood of the strength specimen failing in buckling, an approximate analysis[4] was conducted in which the circular waisted profile was replaced by the idealised profile 'stepped' to a total of three thicknesses. The degree of end restraint was determined by experiment, since it was realised that the end pieces did not produce exactly built-in conditions; in the event only a slight relaxation of the built in restraint was necessary. The calculated buckling stress showed a considerable margin (16:1) over the expected failing load making conservative assumptions concerning the expected modulus[5] for type II composites. Thus, in view of the additional conservative assumptions made in the analysis, buckling was not considered a problem.

Additionally, since a specimen was also required for modulus determination an approximate buckling analysis was also performed on a modified specimen which had a central parallel sided gauge length of 10 mm at the waisted section. As would be expected, this modification had a destabilising effect, and it was concluded that the specimen thus modified would only be suitable for modulus determinations on type I composites. Since the material was expected to be linearly elastic to failure, further modifications to the specimen were not considered of great importance, and it was decided to use a simple unwaisted specimen for modulus determinations. It should be noted, however, that the analysis predicts that an extended waisted specimen could be used satisfactorily for type I composites and to at least 75% of failing load for type II composites.

2.1.2 End fittings

For a given specimen and end fitting configuration and a specified thickness of adhesive the proportion of the compressive load transferred by shear from the end fittings is increased if the shear transfer length (L, Fig.2) is increased with a consequent reduction in the compressive loads at the ends.

In determining the length of specimen to be built in to the end fittings it must be remembered that the stress concentration at the section where the specimen protrudes from the end fittings increases with the shear load transferred; too short a length results either in a 'brushing' failure initiated by the bearing load transferred by compression at the end of the specimen or local yielding of the metallic end pieces. Again a compromise was necessary and a suitable length was determined empirically to be 15 mm. Buckling of the specimen due to lateral freedom within the end fitting would be possible with a thick glue line: however, the thickness chosen (0.025 mm) was sufficiently small for this to be avoided.

The resultant end fitting is shown in Fig.3 and the complete specimen in Fig.4. The end fittings, which were expendable, were machined from standard aluminium alloy bar, the external dimensions of which were chosen to provide adequate reinforcement and facilitate positioning in the test machine.

2.2 Compressive modulus

An unwaisted version of the specimen chosen for the determination of the ultimate compressive strength, with a free length increased to 25 mm, was used for the measurement of compressive modulus. Since the bearing points of standard extensometers lead to stress concentrations which would be unacceptable in CFRP and also require a relatively large gauge length, the strain measurements were made using electrical resistance strain gauges.

3 SPECIMEN MANUFACTURE AND EVALUATION

3.1 Resin impregnated carbon fibre sheet

To eliminate batch to batch variations, one batch only was tested of each of the following types of fibre which were used in the specimen evaluation; high modulus, surface treated (I-S); high strength, surface treated (II-S) and high strength, untreated (II-U). Fibres from these batches were supplied to two commercial organisations for production of preimpregnated sheet using three different resins. As a control, one resin system was used by both organisations for two of the fibre batches. The fibre properties as measured by Materials Department and the resin systems used are given in Table 1. The resin preimpregnated carbon fibre sheets supplied were approximately 1 metre long in the direction of the fibres, 0.3 metre wide, 0.25 mm thick and contained about equal parts by weight of fibre and resin.

3.2 Laminate and specimen preparation

Each sheet was laminated to produce a board 200 mm long (in the fibre direction) by 120 mm wide and 2 mm thick containing approximately 60% fibre by volume. The sheet was cut into 8 plies, each 200 mm by 120 mm which were then laid up on a slightly larger ground steel plate of thickness 20 mm to form a laminate 8 plies thick. To restrain the composite from expanding in a direction perpendicular to the fibres when under pressure, a 10mm wide strip of compressible, absorbent material[*] of thickness slightly greater than the unpressed laminate, was bonded to the plate along the longer sides of the laminate. Three layers of glass fibre cloth (two 0.5mm satin weave and one 0.25mm mock leno weave) impregnated with release spray[**] were then laid over the laminate, the mock leno cloth being at the composite surface to minimise the surface roughness of the cured composite. The purpose of the glass cloth was to absorb an empirically predetermined amount of excess resin and to enable trapped air and volatiles to escape whilst minimising the risk of fibre misalignment due to resin flow. A second ground steel plate was placed on top and metal spacers 2 mm thick inserted between the edge regions of the plates. Where the resin system so required, the laminate was pre-cured in an air circulating oven before insertion in a pre-heated press. Light pressure was applied until resin gelation and the pressure was then slowly increased, the spacers serving as a thickness control. After moulding, the laminate was post cured in an air circulating oven, the cure cycles for each resin being given in Table 2.

The glass cloths, now impregnated with resin, were removed and specimens cut from the board using a band saw, the specimen surfaces being finished with wet and dry emery paper to give final dimensions of 47 mm (in the directions of the fibres) by 10 mm wide by 2 mm thick. The compressive strength specimens were then waisted to the dimensions given in Fig.4 using a 125mm radius grinding wheel. In addition to the specimens laminated from resin preimpregnated sheet, comparative specimens from each batch of fibre were made by the flow control technique using 828/MNA/BD resin. The fibre volume fraction of each laminate was determined using the standard wet combustion technique[6].

3.3 End fittings

The end fittings, illustrated in Fig.3, were accurately machined from standard aluminium alloy L65 bar. These were bonded to the specimen in a

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[*] Scotchbrite, very fine pads. Minnesota, Mining and Manufacturing Co.

[**] Rocol, non-silicone, dry film release spray.

jig, Fig.5, to ensure accurate alignment, retaining pressure being applied in the directions shown. To provide adequate restraint against buckling a high modulus adhesive* was used. The thickness of the composite varied to some extent between specimens but the dimensions of the end fittings were maintained constant for ease of fabrication: where appropriate, steel shims were inserted between the end fittings and the specimen to reduce the glue line thickness.

3.4 Testing

Specimens of each fibre/resin/preimpregnated sheet manufacturer combination were carefully aligned and tested between the platens of an Avery universal testing machine (maximum load 150 MN m^{-2}). The compressive strength specimens were loaded at a strain rate sufficient to produce failure in approximately 30 seconds. Stiffness determinations were made using foil electrical resistance strain gauges** in a conventional Wheatstone bridge, the out-of-balance voltage being measured on a high impedance digital voltmeter.

4 RESULTS

The ultimate compressive strengths determined are given in Table 3 together with the fibre volume fraction of each laminate and the shear strength determined by the standard 3 point bend test[7]. For purposes of comparison the average composite strengths have been converted to fibre stresses using the known laminate volume fractions.

Typical specimen failures for the three types of fibre used are illustrated in Figs.6, 7 and 8. With the exception of the slight brushing on the type II-U specimens, the compression failures were similar and showed an initiation point in the region of minimum thickness. In a few specimens, failures adjacent to the end fittings occurred; this appeared to be associated with inadvertent violation of the 1.5 waisting factor and the values obtained, based on the minimum cross section were assumed to represent the true compressive strength of the material. It may be seen in Table 3 that, in general, little variation of ultimate compressive stress occurred between nominally similar specimens.

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[*] CIBA Resin AV100 + hardener AV100. Equal parts by volume.

[**] Welwyn Electrical Co Ltd. EA-06-125/T120 bonded with resin CIB MY 753/HY 951

Stress-strain curves were found to be linear in the stress range used with the unwaisted specimens and the stiffnesses are given in Table 4.

5 DISCUSSION

Use of a single batch of fibre of each type throughout enables the influence of resin, preimpregnated sheet manufacturer and laminating technique to be readily assessed without the additional variations which are likely to arise between fibre batches. To allow approximate comparisons to be made also between fibre types, the average compressive fibre stresses at failure obtained in the experiments have been converted to relative fibre efficiency, $\left(= \frac{\text{average compressive fibre stress}}{\text{ultimate fibre stress}} \right)$ using the ultimate tensile strengths of the fibres, Table 1, as a basis; these efficiencies are given in Table 3.

It can be seen that neither resin, manufacturer nor method of composite fabrication shows any consistent effect on the ultimate compressive strength. The only consistent variation in strength was between fibre types, showing possible correlation with shear strengths determined for the same composite boards and also given in Table 3 (see Fig.9).

The compressive failure of an idealised composite by elastic buckling of the fibres has been analysed by Dow[8] who has shown that for the volume fractions considered here the mode of buckling is such that the resin deforms purely in shear. The failure load is then given by

$$\text{Composite ultimate strength} = \frac{\text{matrix shear modulus}}{\text{matrix volume fraction}}$$

This simple theory predicts strengths several times higher than those achieved in practice. Several reasons for this high theoretical prediction have been proposed[1]. For example, a buckling mode with a lower failure stress might well occur since the assumptions of uniform volume fraction and straight, evenly spaced and parallel fibres are not valid for CFRP. Such considerations are however unlikely to account for a discrepancy of this order and it is more likely that the strength of the constituents or of the bond between them is exerting a major influence.

If as the theory suggests, the compressive load is ultimately limited by the shear modulus of the resin, it may be postulated that the shear strains caused by buckling fibres would induce premature failure of the fibre/matrix interface in weakly bonded composites. Fig.9 is an attempt to correlate the compressive strength (represented by the compressive fibre efficiency) with the composite shear strength. It will be seen that a strong relationship seems to exist over a relatively wide range (23 MN m^{-2} to 86 MN m^{-2}) of shear strengths, reduced shear strength implying reduced compressive strength. Since no correlation of compressive strength with matrix modulus is apparent (see Table 3) it may tentatively be suggested that, although insufficient is yet known about the compressive failure mechanism, the composite shear strength appears to be a critical parameter. This in turn suggests that compressive failure may follow from failure of the resin/fibre bond at some point in the composite.

The strengths reported here for the type I-S material are similar to those obtained using the circular test specimen[1], the only disadvantage being the inability always to use the flat specimen for modulus determinations to failure. The composite stiffnesses are compared, in Table 4 with those obtained from the fibre modulus to give a fibre efficiency. Again, the relatively low efficiency of the type I-S fibre may be noted.

6 CONCLUSIONS

The ultimate compressive strength of CFRP boards laminated from resin preimpregnated carbon fibre sheet may be determined with confidence using the relatively inexpensive specimen described which, in general, fails at the minimum cross section and which gives values of ultimate strength consistent with known material properties. A similar specimen has been shown to be adequate for the measurement of elastic stiffness in compression.

Tests conducted to evaluate the strength specimen have indicated also that composite compressive strength increases with composite shear strength, suggesting that compressive failure follows from local failure of the resin/fibre bond.

Table 1

FIBRE TYPES AND RESIN SYSTEMS

Fibre type	Ultimate tensile strength MN m^{-2}	Tensile Modulus GN m^{-2}	Manufacturer	Resin system
I-S	1606	490	A	ERLA 4617/DDM 828/DDM/BF3
			B	828/DDM/BF3 DLS 60
II-S	2248	287	A	ERLA 4617/DDM 828/DDM/BF3
			B	828/DDM/BF3 DLS 60
II-U	2799	278	B	DLS 60

Table 2

RESIN CURE CYCLES

Resin system	Pre-cure		Press		Post-cure	
	Temperature °C	Time h	Temperature °C	Time after gelation h	Temperature °C	Time h
ERLA 4617/DDM	120	0.7	160	1.5	170	16
828/DDM/BF3	NIL	NIL	160	1	170	2
DLS 60	NIL	NIL	160	1	150	1

Table 3

COMPOSITE COMPRESSIVE STRENGTH

Fibre type	Resin system	Manufacturer	Fibre volume fraction	Number of specimens	Strength $MN\ m^{-2}$			Average fibre Stress $MN\ m^{-2}$	Relative fibre efficiency e%	Composite shear strength $MN\ m^{-2}$
					Min	Ave	Max			
I-S	ERLA 4617/DDM	A	0.61	5	391	503	602	834	52	47.2
	828/DDM/BF3	A	0.63	4	484	574	623	953	59	36.2
	828/DDM/BF3	B	0.57	5	528	581	608	965	60	39.0
	DLS 60	B	0.55	4	582	601	622	998	62	45.3
	828/MNA/BD	RAE	0.60	3	556	568	587	943	59	58.4
II-S	ERLA 4617/DDM	A	0.62	3	1084	1260	1367	2092	93	59.9
	828/DDM/BF3	A	0.67	3	1140	1174	1214	1949	87	71.6
	828/DDM/BF3	B	0.56	4	1097	1160	1234	1926	86	60.7
	DLS 60	B	0.53	4	946	1023	1091	1699	76	60.5
	828/MNA/BD	RAE	0.66	3	1264	1384	1482	2298	102	85.9
II-U	DLS 60	B	0.56	4	834	870	911	1445	52	23.0
	828/MNA/BD	RAE	0.60	3	722	771	805	1280	46	33.7

Table 4

COMPOSITE COMPRESSIVE STIFFNESS

Fibre type	Resin system	Manufacturer	Fibre volume fraction	Maximum applied stress MN m^{-2}	Stiffness GN m^{-2}	Fibre stiffness GN m^{-2}	Relative fibre efficiency e%
I-S	828/DDM/BF3	A	0.63	210	267	490	86.5
II-S	828/DDM/BF3	A	0.67	370	175	287	91

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No.	Author	Title, etc.
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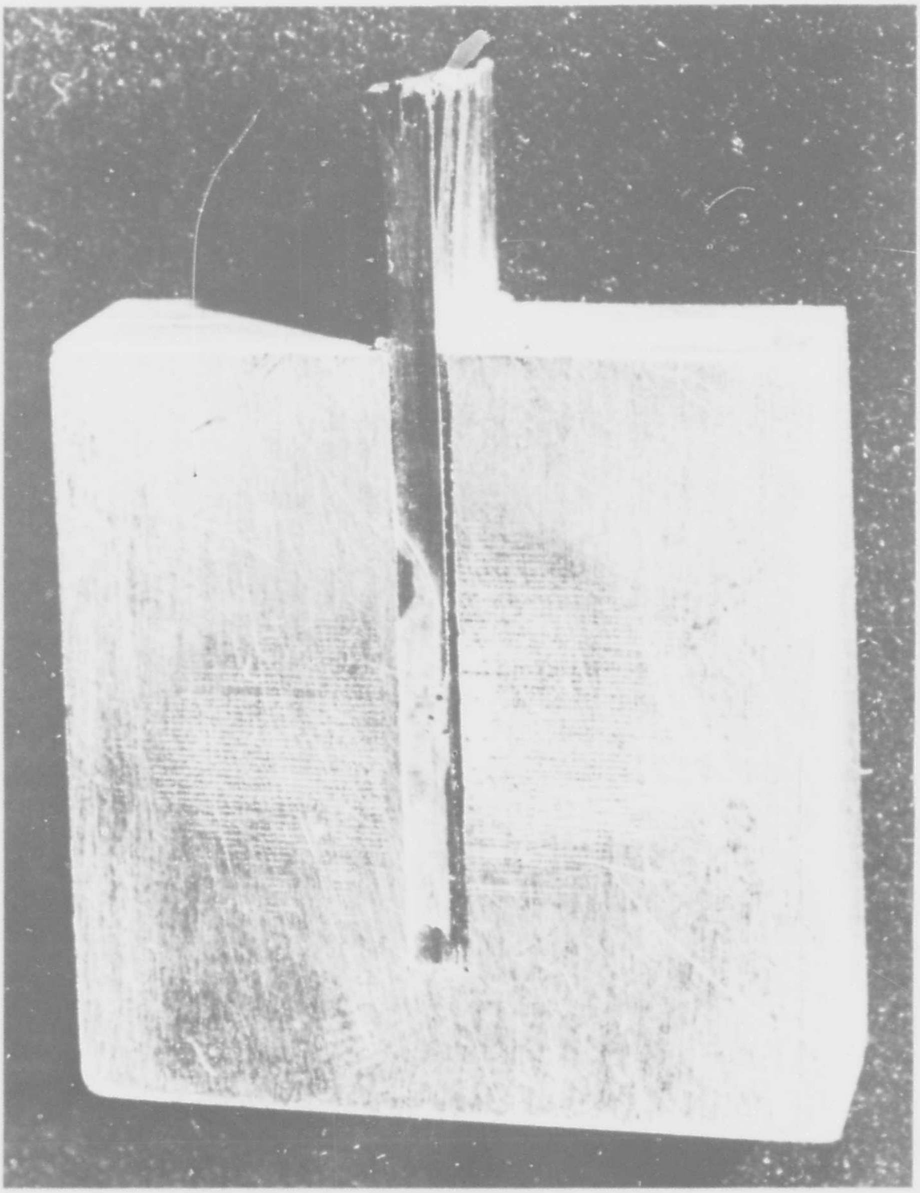

Fig.1 Brushing of unreinforced end

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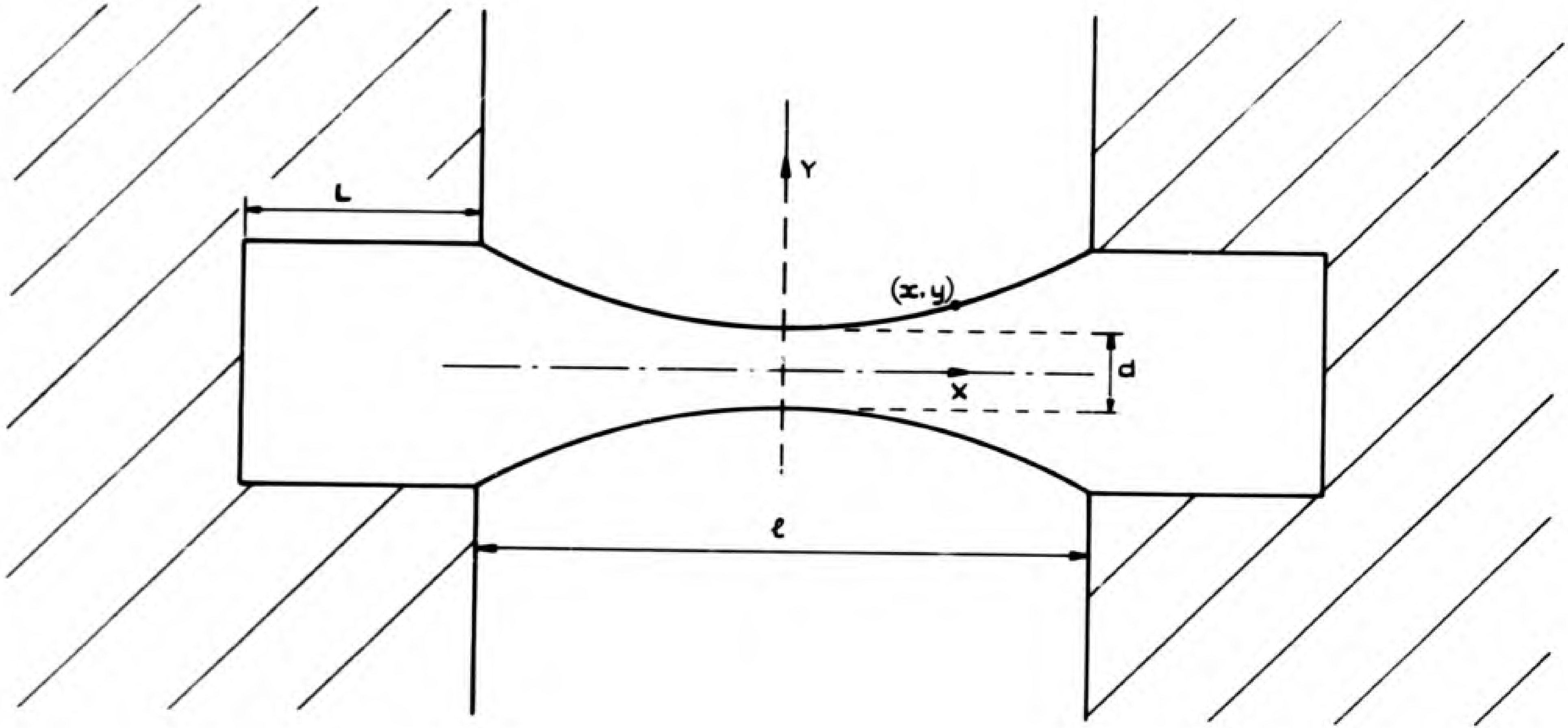
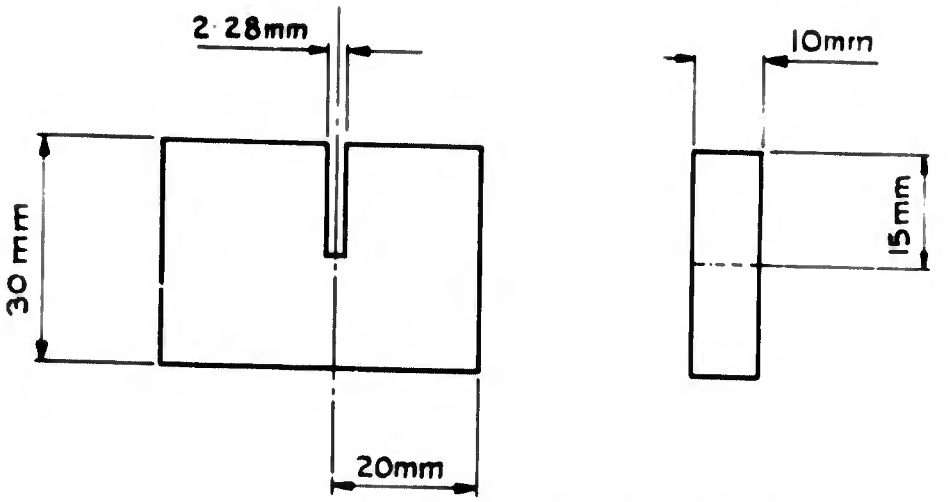


Fig. 2 General specimen configuration



Material Aluminium alloy to specification L65

Fig. 3 Longitudinal compression end fitting

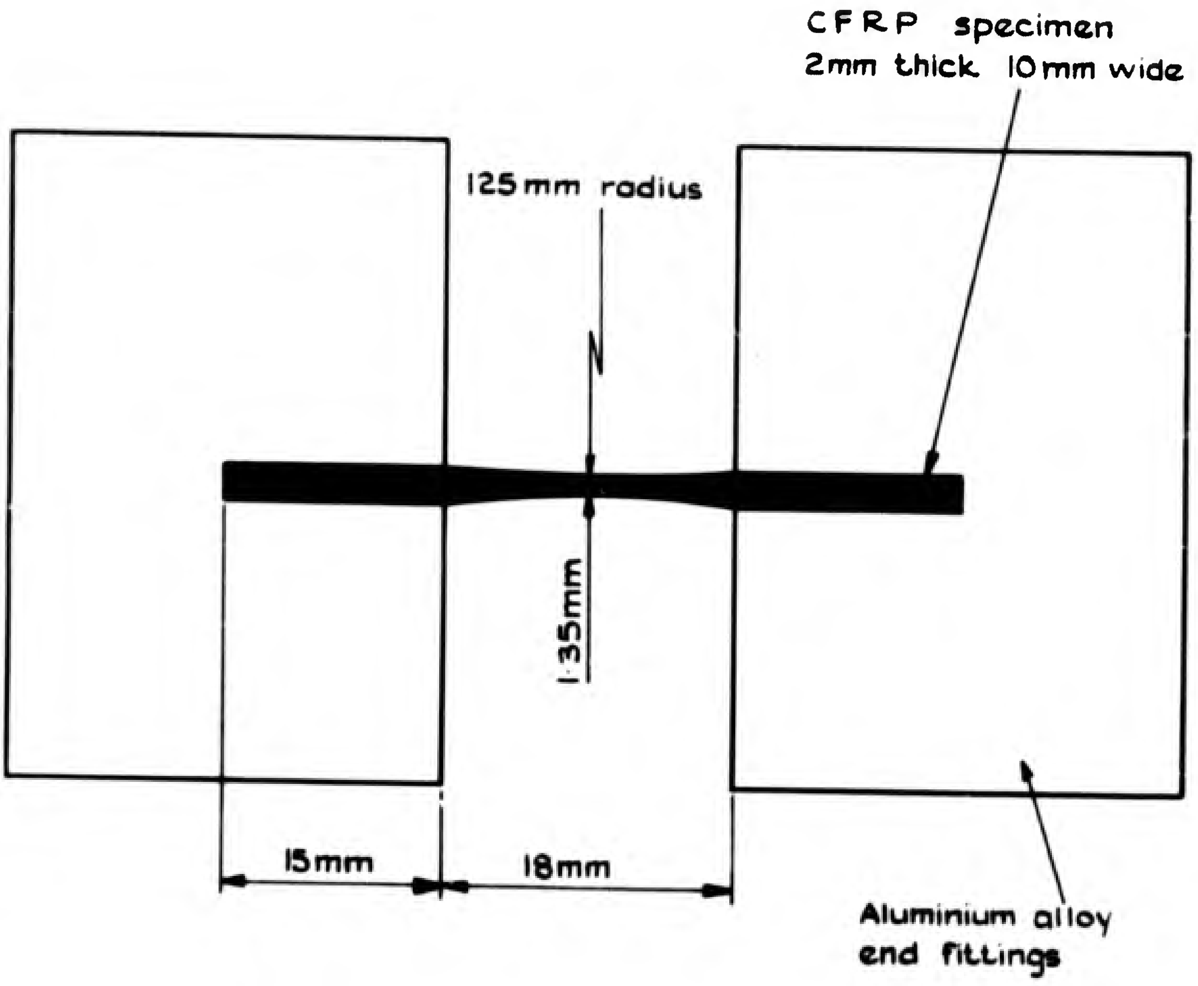


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Fig. 4 Longitudinal compression test specimen

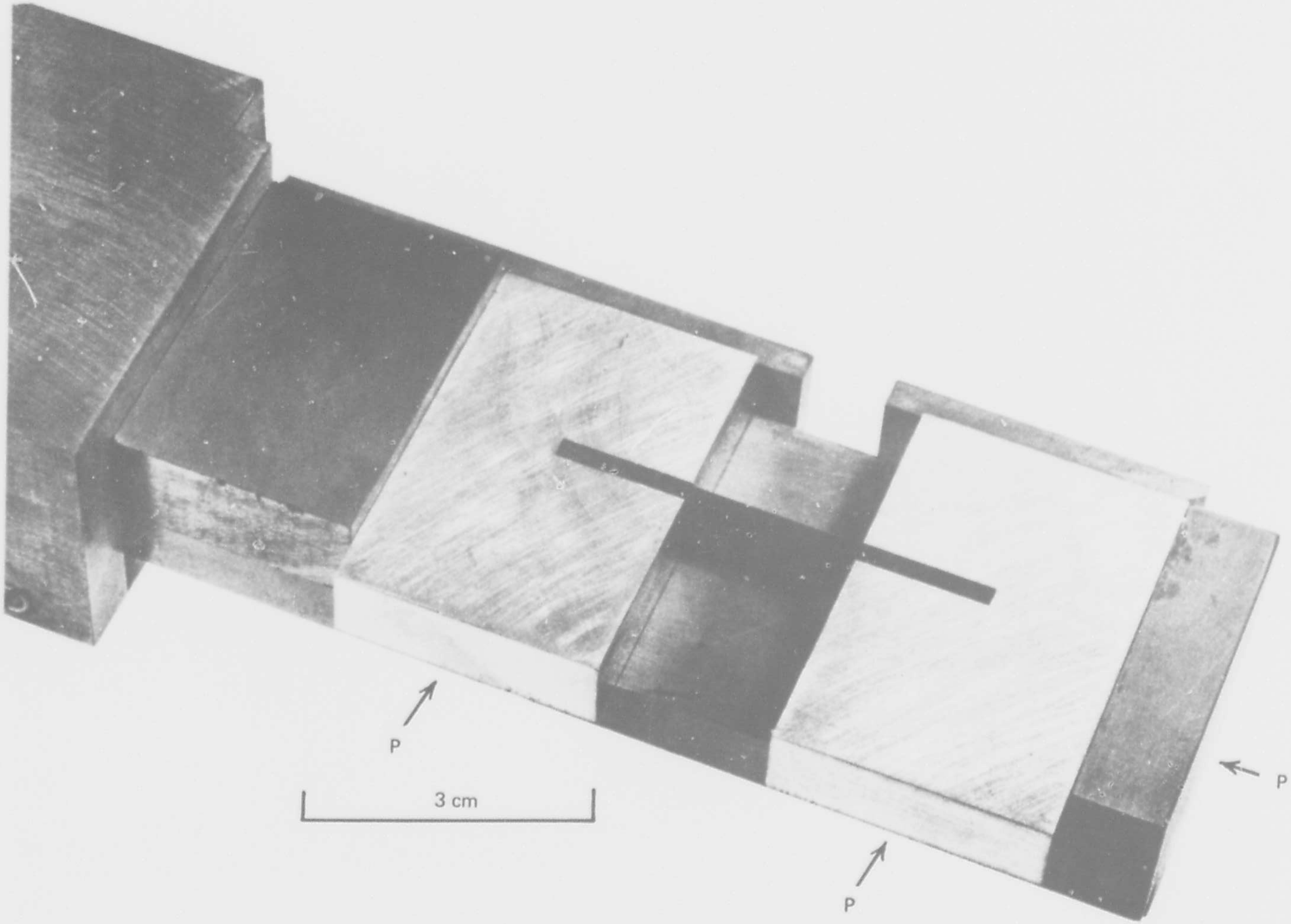
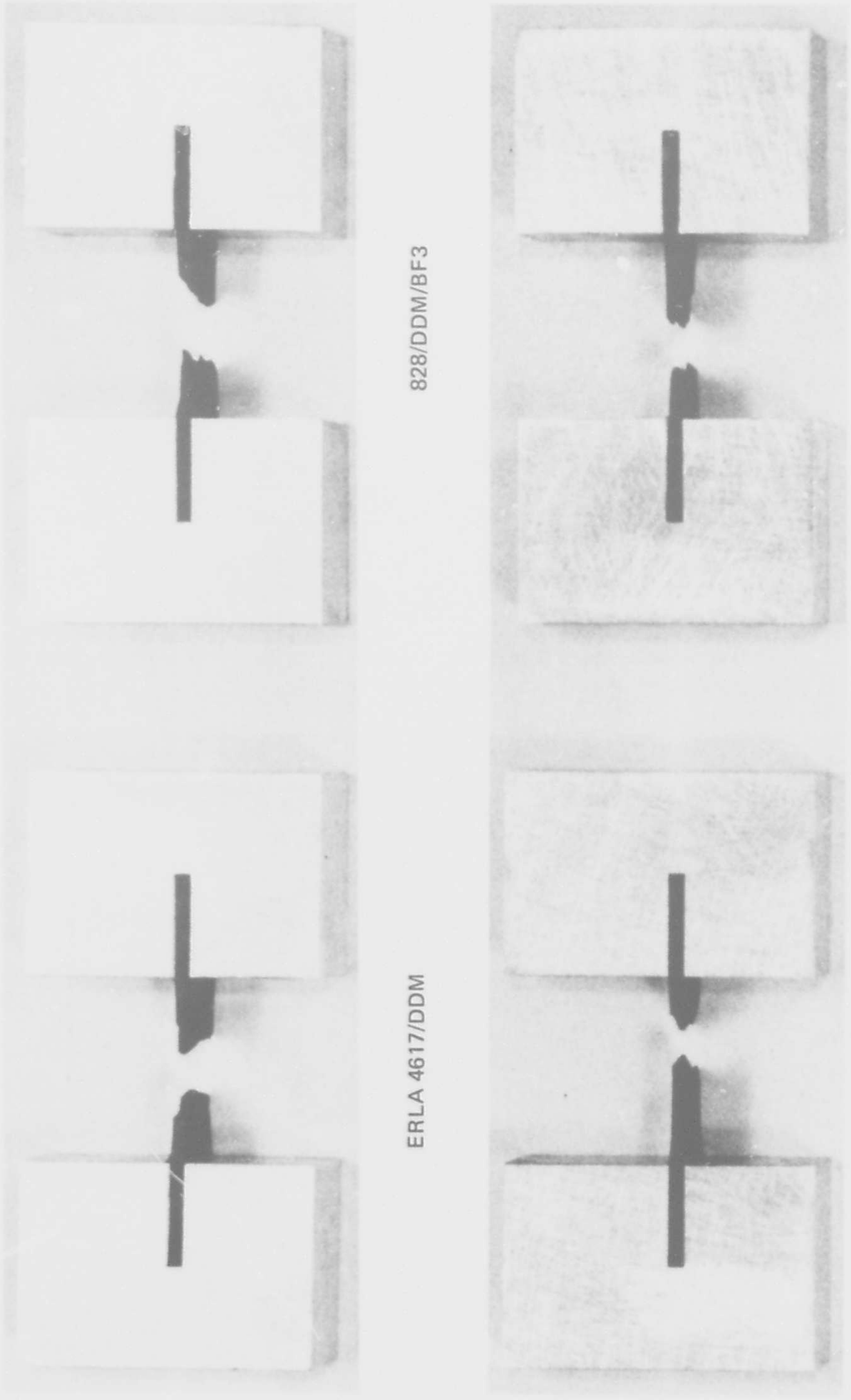


Fig.5 End fitting alignment jig (retaining pressure, P)



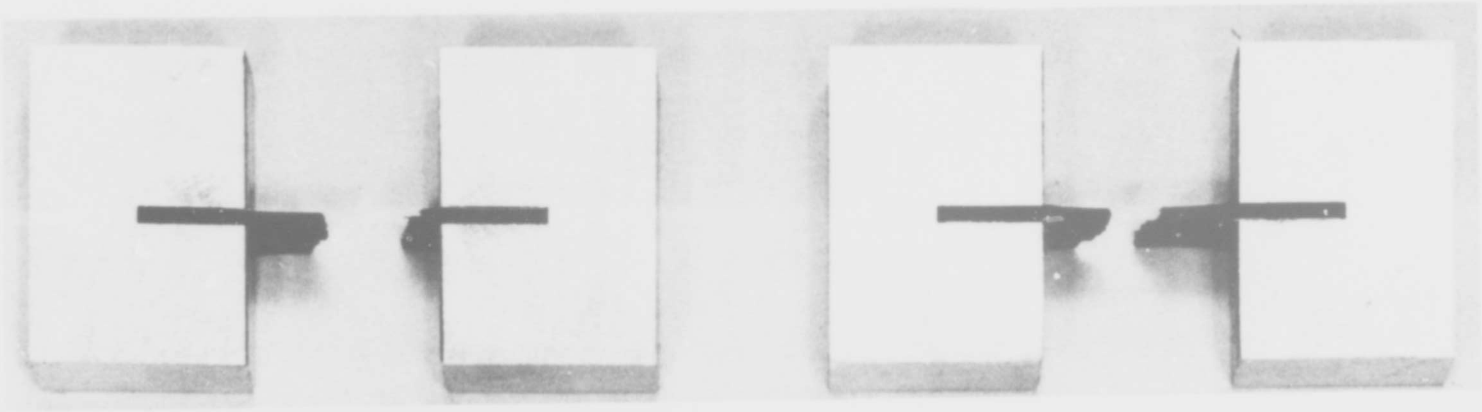
828/MNA/BD

DLS 60

828/DDM/BF3

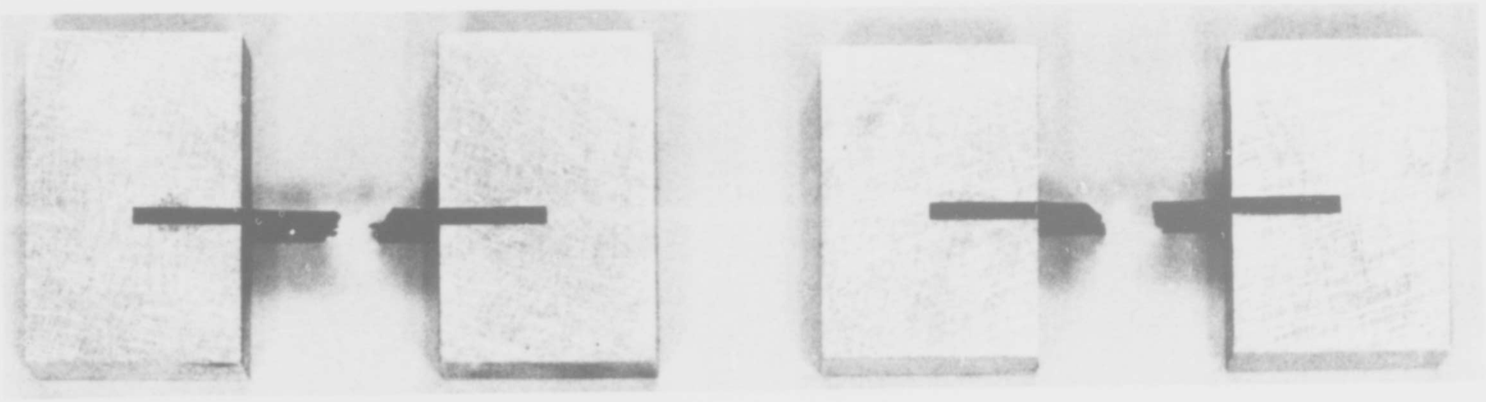
ERLA 4617/DDM

Fig.6 Typical failures, Type I-S fibre



ERLA 4617/DDM

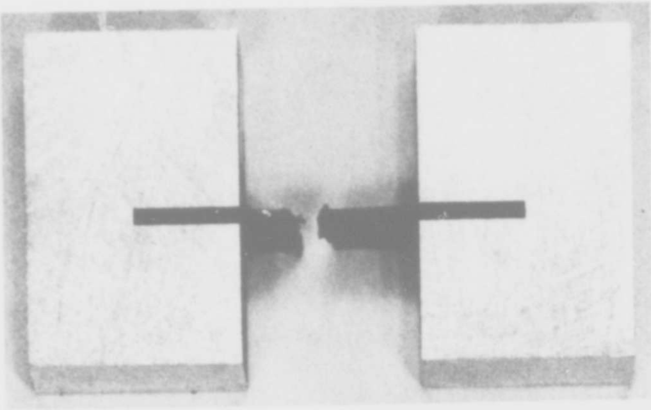
828/DDM/BF3



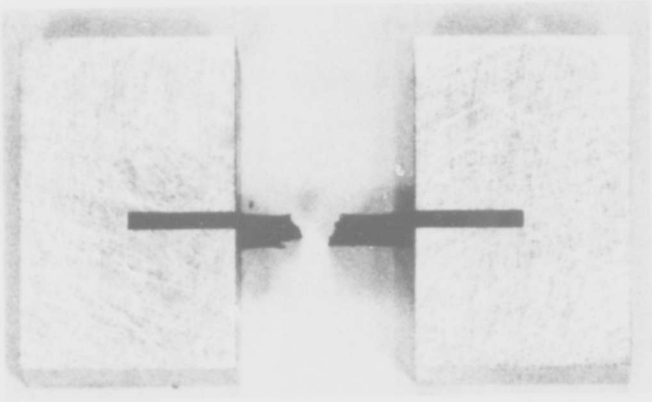
DLS 60

828/MNA/BD

Fig.7 Typical failures, Type II-S fibre



DLS 60



828/MNA/BD

Fig.8 Typical failures, Type II-U fibre

Fig. 9

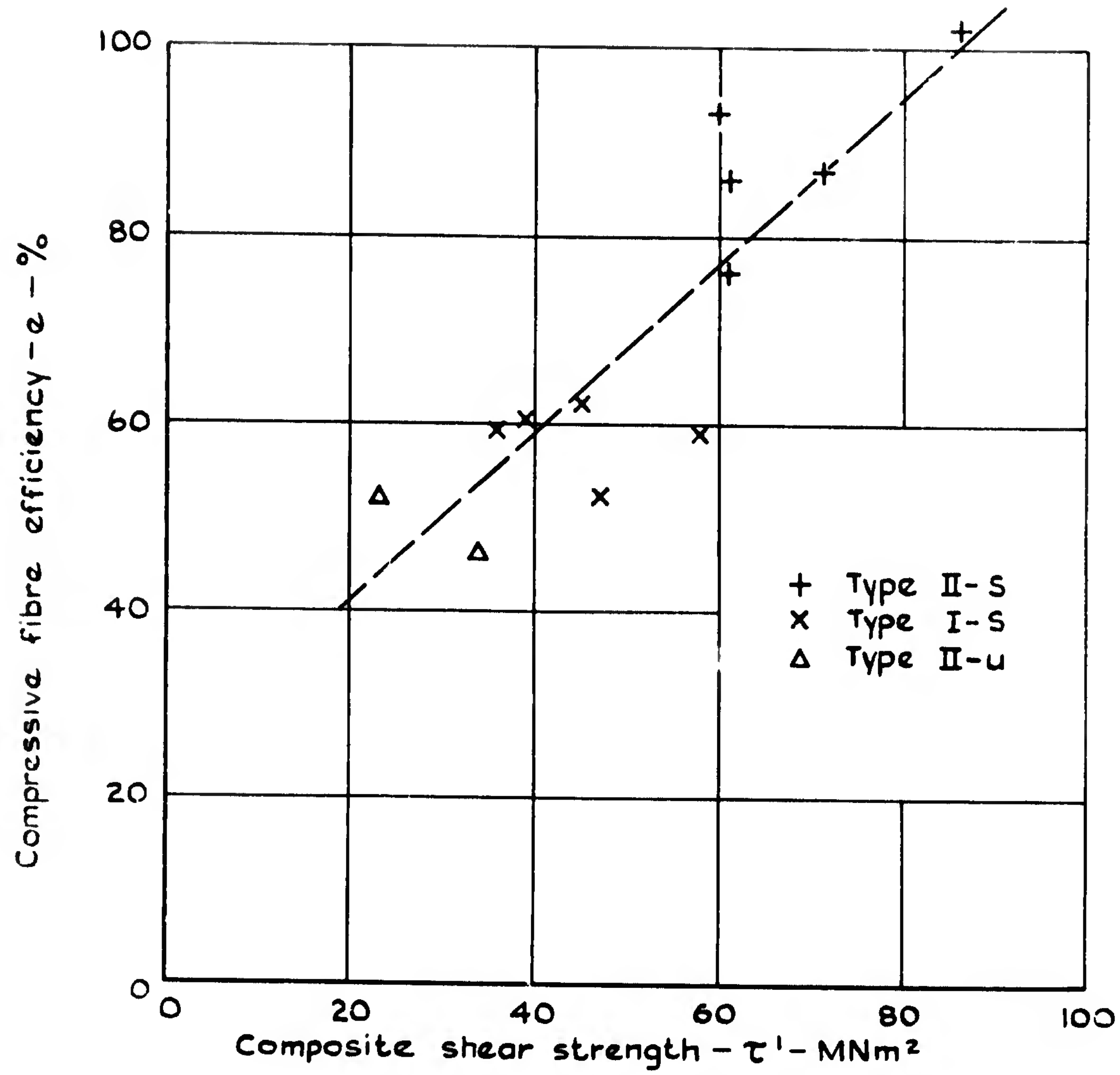


Fig. 9 Effect of shear strength on compressive fibre efficiency