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The Shear Properties of Unidirectional Carbon Fibre Reinforced Plastics and their Experimental Determination

by

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THE SHEAR PROPERTIES OF UNIDIRECTIONAL CARBON FIBRE REINFORCED PLASTICS

AND THEIR EXPERIMENTAL DETERMINATION

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SUMMARY

Various techniques for the prediction and measurement of the shear strength
and stiffness of unidirectional carbon fibre composites have been compared and
evaluated.

The Report concludes that the shear modulus, but not the shear strength,
may be predicted with sufficient accuracy for most practical purposes and
recommends satisfactory methods for the experimental determination of shear
modulus and strength.

CONTENTS

1   INTRODUCTION

The development of advanced fibre reinforced materials having high specific strength and stiffness has provided the designer with considerable potential for weight saving, particularly in the aerospace field. The advent of these composites has also allowed greater flexibility in the design of such lightweight structures. No longer is it necessary to commence with a known material of specific properties; by selection of fibre and matrix in appropriate proportions the properties of a unidirectional fibre reinforced material may be controlled. Combining laminae of such unidirectional material at differing orientations then allows the production of laminates having the desired strength, stiffness and degree of anisotropy.

A necessary precursor to the effective design of lightweight structures using fibre reinforced plastics is a reliable knowledge of the elastic constants and strength properties of the unidirectional material. Simple determination methods for such properties as shear strength are also useful qualitative tools in the composite materials development and production fields. Satisfactory techniques for the determination of the properties of isotropic materials have been in existence for many years. The use of highly anisotropic materials, however, has brought the need for new methods of material characterisation and also a requirement for a larger number of material parameters to define fully their characteristics than are necessary for conventional structural materials.

In a series of RAE Technical Reports on unidirectional carbon fibre reinforced plastics (CFRP) in the form of flat laminates, experimental test specimens and techniques have been described[1-5] for the determination of materials data under longitudinal and transverse tension and compression. A multitude of methods has been recommended in the literature for the determination of the shear strength and stiffness of unidirectional composites. One of the major problems in shear testing, particularly in the determination of strength, is the influence of stresses other than shear on the properties measured. None of the methods in practice induces a state of pure shear and not all allow determination of both strength and stiffness. The selection of test technique will also be influenced by the method and ease of specimen fabrication and the requirement of any special test facilities. In addition, the plane in which the shear response is required will also restrict the choice of method.

From a consideration of the general conditions necessary for a satisfactory shear test and an evaluation of the available techniques, several of the most

promising and applicable methods were chosen for detailed experimental evaluation. This Report describes tests commonly known as 'plate twist', 'rail', 'short beam', 'transverse compression' and 'tube' and investigates their advantages and disadvantages.

Since the above selected methods did not allow the measurement of the 'interlaminar' shear modulus, a simple experiment to determine the relative shear stiffnesses in the three principle planes is also described. The experimental results obtained are presented together with recommendations of suitable test techniques. A discussion of the many theoretical analyses for the prediction of shear modulus and strength results in the recommendation of a simple, accurate method for the calculation of shear stiffness from the constituent material properties. Whilst an effective method of predicting shear strength is not available, the analyses highlight the factors affecting the failing stress.

2   GENERAL CONSIDERATIONS

2.1   Ideally homogeneous laminates

It has been said that the true shear properties can only be obtained when the material is under a state of pure shear[6]. That this truism needed to be stated is a reflection of how far some common test methods deviate from the ideal. However, taken to the extreme, this statement would preclude any practical determination of the properties of real composites.

In order to understand how the problems arise consider first an ideal laminate: a flat, square, homogeneous plate of uniform thickness and side length (ℓ), subject to an evenly distributed pure shear stress, τ , producing a small strain ϕ (Fig.1). If the fibre/resin geometry and interaction, and inter-laminar discontinuities are ignored and the unidirectional composite is assumed to be a homogeneous orthotropic material, there are three planes of material symmetry as given in Fig.2. The fibre direction is taken as the '1' axis and the '3' axis is the direction of the laminating pressure; that is to say plane 3 (the plane perpendicular to the 3 axis) is the plane of the laminae. Hence, three planes of shear stress may be defined as longitudinal or in-plane (τ_{12}), transverse (τ_{23}) and interlaminar (τ_{13}) and the corresponding moduli as G_{12}, G_{23} and G_{13} . The meaning of these definitions may be clarified by illustrating the strains produced by these stresses (Fig.3). In practice, the longitudinal shear properties govern the design of typical skin construction: the interlaminar shear strength may limit the detailed load transfer mechanism at joints and the bending strength of unidirectional laminates under non-uniform load. Cases where the transverse shear properties are of significance are seldom encountered.

For unidirectional composites, which are the primary concern of this Report, the shear stresses and strains may be regarded as positive irrespective of direction, but the reader's attention is drawn to the fact that in stress analyses, particularly with off-axis laminates, the use of a sign convention such as that given by Pagano and Chou[7] is imperative.

2.2 Non-homogeneous laminates

In practice, the above ideal assumption that the laminate is perfectly homogeneous will not be true due to imperfections such as poor lamination, variation in fibre volume fraction and fibre alignment, and voids. For a unidirectional material such a discontinuity will induce what may be regarded as a plane of weakness parallel to the fibres and passing through the discontinuity. Hence under a uniform shear stress τ the plate will deform as shown in Fig.4. In a real material there will be many such discontinuities but only when the strain ϕ is small will δx be small compared to $\delta \ell$. It follows that such effects may be ignored when determining the material modulus (i.e. the tangent modulus at zero stress) if the total strain over the length ℓ is measured. If, on the other hand, the strain is measured over a relatively small area the measured modulus may be lower than the overall modulus if a plane of weakness passes through that area.

These planes of weakness become of considerable importance when discussing the determination of shear strength. When measuring a uniaxial strength such as in transverse tension $(\hat{\sigma}_2)$, the maximum stress may be considered to be that of the weakest link in a chain where a crack may progress from a discontinuity without hindrance from the loading attachments. In order to apply a similar uniform shear stress to the plate (Fig.4) it is necessary to imagine hypothetical attachments along edges ABCD which allow deformations, δx , to occur unhindered whilst maintaining a uniform stress along A'D and B'C. Sudden failure would then occur along the weakest line at a stress $\hat{\tau}_{min}$ which is that of the weakest link.

If the imagination is now turned to equally hypothetical attachments of infinite stiffness such that sides ABCD are constrained to remain straight, deformations such as δx along planes of weakness cannot take place. The stress along edges A'D and B'C will be non-uniform and a crack originating at a discontinuity will progress until the redistribution of stress is sufficient to prevent crack growth or the crack reaches the attachments. In either case there may be no detectable change in sustainable load since, apart from the slight redistribution of stress at the free edges along the crack, even when the crack reaches the attachment the plate A'B'CD merely behaves as two strips A'B'E'F' and

EFCD (Fig.4) capable of reacting approximately the same load. The plate will thus continue to sustain increases in load and more cracks until the size and number of strips, n , is such that they fail in bending. At this point elementary bending theory gives the measured 'shear' strength as

$$\hat{\tau}_{max} = \frac{n}{3} \hat{\sigma}_1$$

and the 'shear' strain as

$$\phi = \tan^{-1} \frac{\ell\hat{\sigma}_1^3}{54E\hat{\tau}^2} \quad . \tag{1}$$

In this case the failure is not due to shear alone, the shear stresses are non-uniform, $\hat{\tau}_{max}$ may be considerably greater than the previously defined $\hat{\tau}_{min}$ and the material has failed in many places before final collapse.

Practical test configurations provide loading arrangements varying widely between these hypothetical extremes and hence measure shear strengths of significantly different magnitude. Furthermore it will be clear from the above that the shear modulus and strength will be dependent on whether the stress mode is longitudinal, transverse or interlaminar and experiments reported here and elsewhere[8] have confirmed that the results from the three modes are different. Cases also arise where the fibre axes rotate relatively.

2.3 Shear stress distribution

2.3.1 Non-uniform stress

In several test methods, particularly those involving torsion of a solid member, conditions arise where although the stress mode is pure shear, its intensity varies through the specimen cross section. The plastic matrices are rarely, if ever, linearly elastic to failure and hence the measured strain at the surface will not be simply related to the applied load. For the determination of initial modulus acceptable results may be obtained using a simple relationship as long as the stresses are kept very small. Mathematical methods of determining the tangent modulus to failure for non-linear conditions have been evolved[9] but the results are difficult to interpret. In some cases the shear distribution is hard to determine, making modulus determinations inaccurate and any measured strength of questionable value.

2.3.2 Combined stresses

In most of the available shear test methods, stress modes other than shear are manifest. The question therefore in choosing a suitable method is not so

much one of whether shear is the only mode present, but how important is the presence of another mode. For instance, the existence of a relatively low axial tensile stress is unlikely to affect the measurement of shear stiffness or strength. On the other hand, in shear tests involving bending, the specimen may fail in flexure before the ultimate shear strength is reached. Similarly, it has been shown[1,8] that a relatively small transverse compressive or tensile stress will significantly alter the measured shear strength. In addition, Hayashi and Koyama[10] suggest from limited data that the shear modulus of an epoxy matrix varies with compressive stress. Thus the composite shear modulus may also vary with transverse stress.

2.3.3 Stress concentrations

Whilst in many tests it may be shown that over a relatively large area of the specimen the shear stress is acceptably pure and uniform, concentrations of stress frequently occur, for example, at the edges of the specimen or at the points of load application. In such cases the measurement of strain over the area of known uniform stress will provide an accurate measure of the shear modulus. However, the stress concentrations may initiate failure at a stress below the ultimate shear strength of the material and thus make the methods of uncertain value for the measurement of strength. This aspect is of particular importance since many of the simpler tests designed to measure only strength suffer from such effects.

2.3.4 Stability

In cases where the specimen thickness is small compared to some linear dimension, such as in thin-walled tubes or thin flat plates, buckling may influence the determination of the tangent modulus or precipitate early failure. The problem is an inherent one, and can only be accommodated by appropriate specimen design.

2.4 Loading rates

In ancillary experiments[11] to those described in this Report it was shown that little shear stress-relaxation and hence viscoelastic shear strain occurs at stress levels below about one third of the composite ultimate shear strength. However, above this level the measured modulus and strength may be significantly reduced by prolonged or repeated stressing. In order to obtain an accurate measurement of the tangent shear modulus to failure, or simply a reliable strength determination, the loading rate should be such as to produce failure within 3 to

6 seconds. For these purposes it is thus clear that manually read, repeated loading experiments are inadequate and automatic load/strain equipment must be employed.

2.5 Practical laminates

The composites tested were fabricated from sheets of resin preimpregnated carbon fibre and hence the test methods chosen had to be applicable to such laminates. The applicability of the methods to material characterisation programmes also means that the cost in terms of material quantity, specimen preparation, and instrumentation and test facility complexity should be minimal consistent with the determination of meaningful properties. This biases the choice of method towards small flat specimens, which for strength determination may be failed in a simple rig in an existing universal test machine and for modulus measurement require only the provision of a strain transducer and recorder.

3 SELECTION OF TEST TECHNIQUES

The shear testing of fibre reinforced materials has been carried out for many years using techniques from the simply crude to the highly elaborate. A literature survey revealed a plethora of existing methods which are best dealt with by tabular summarization (Table 1). Each method is referred to by its most frequently used title and the technique involved represented in the respective illustrations Figs.5 to 7. Minor variations in technique which are not considered significant are omitted. The methods are broadly grouped according to the specimen geometry. The primary shear mode tested and the suitability for strength or stiffness determination are listed together with a brief assessment of the technique and a column of relevant references.

3.1 Flat specimens

Acoustic and resonance techniques, which appear to offer reliable means of measuring shear modulus, are not considered in this Report since suitable test facilities are unlikely to be generally available. The notch, punch and slip-plane methods all suffer from serious stress concentrations and specimen preparation for the I beam experiments are considered too elaborate and showed little advantage over other simpler methods. The in-plane deformation occurring in off-axis tension specimens is reckoned to influence the measurement of modulus and, together with the transverse tensile stresses may give a considerably reduced measured ultimate shear strength[6,12-22]. The picture frame technique has been

analysed in detail[23] and shown to suffer from serious stress concentration and buckling problems, although Dickerson and Dimartino[24] claim to have overcome some of these using a complicated test rig.

For the measurement of modulus alone, the plate twist test offers most promise if executed within the necessary deflection limits[25-27]; it also has the advantage that the same specimen can be subsequently tested by other methods and so, for example, allow simple shear strength measurements by the short beam test. It has been shown[28] that the stress concentrations in the rail test are much reduced when conducted with the axis of the fibres perpendicular to the rails and the method may therefore be suitable for the measurement of both strength and modulus. Very significant stress concentrations exist in the short beam specimen and it is not always possible to ensure a shear failure[29-31] thus it may provide only a lower limit on the shear strength. At the other extreme, the transverse compression test is likely to provide an upper limit due to the enhancing of the shear strength by the compressive forces[1].

3.2 Wound or cylindrical specimens

Torsion of a solid rod has been used[9] to measure stiffness and strength but like the beam torsion methods, suffers from non-uniform and usually unknown stress fields. Of all techniques the thin-walled tube with its uniform stress distribution is most likely to give meaningful measurements of strength and stiffness[32,33]. Although the circumferentially wound tube is to be preferred, for practical fabrication reasons only tubes in which the fibres were aligned axially could be considered.

3.3 Angle-ply laminates

Although there is evidence[34,35] that tension tests on $\pm 45^o$ laminates may yield satisfactory values of longitudinal shear modulus, the ultimate shear strengths obtained may be unrepresentative of unidirectional material. Tests of angle-ply laminates were not carried out since they were not compatible with the general set of unidirectional specimens (see section 1).

It should be noted here however that laminated plate theory (e.g. Ashton et al.[36] and Bishop[37]) for angle-ply material does give an indication of the significance of the misaligned fibres which occur in a nominally unidirectional laminate. For example, fibres aligned at $\pm 5^o$ to the unidirectional material will increase the composite modulus by up to 20% depending on the proportion of misaligned fibres.

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3.4 Methods chosen

The selection of methods was based on their compatibility with specimens laminated from resin preimpregnated carbon fibre sheets, the simplicity of the method or the closeness of the stress field to a pure shear case. The techniques chosen for experimental evaluation were therefore (1) plate twist, (2) rail, (3) short beam, (4) transverse compression, and (5) thin-walled tubes.

4 EXPERIMENTAL PROGRAMME

4.1 General

The primary objective of the experimental programme was to examine the suitability and accuracy of the selected tests for the measurement of the shear moduli and strengths of unidirectional carbon fibre reinforced plastics. To minimise possible test variables the specimens were to be fabricated from two batches only of commercial resin preimpregnated carbon fibre sheet, one batch using type I and the other type II fibre, both with the same resin system. For reasons which will become apparent later, a limited number of tests were carried out using a second high strength resin system.

The shear test methods chosen fall easily into two groups: those using flat laminates and those using thin-walled tubes. In order to obtain a direct comparison between the flat laminate methods, each specimen was subjected in turn to the plate twist (modulus only) and rail tests (modulus and strength); short beam and transverse compression strength tests were performed on specimens cut from areas of the laminate adjacent to the plate twist specimens.

4.2 Plate twist

A square plate loaded as shown in Fig.8 forms the basis of the plate twist test. If the three supports at A, B and C are fixed, then the deflection, x , of corner D due to load P has been shown[27] to be given by the relationship

$$G = \frac{3P\ell^2}{t^3 x} \qquad (2)$$

where G is the shear modulus,

ℓ is the side length,

and t is the plate thickness.

Using classical laminated plate theory Whitney[38,39] has shown that the method is only valid for truly homogeneous orthotropic materials (and 0 + 90° equivalent laminates) and that measurements on $\pm45^o$ angle ply plates are in serious error.

Furthermore, not only is the above relation developed from linear small deflection theory but when the corner deflection exceeds several plate thicknesses a point of instability will be reached[26]. This instability will be strongly influenced by any initial curvature of the plate. An additional drawback is that the modulus is a function of the plate thickness cubed and hence the thickness must be uniform and accurately known. It should also be noted that the shear stress mode is of a 'rotational transverse' nature.

The experimental set-up is shown in Fig.9. The plate is 70 × 70 × 2mm and is supported at the corners by three domed pillars which are slightly grooved to provide some stability. Corner deflection was measured using a linear transducer and incremental dead weight load was applied via the transducer probe. The Hewlett-Packard linear displacement transducer (type 7DCDT100) was mounted above the plate so that the transducer core rested on the free corner of the plate. The dc output from the transducer was measured using a digital voltmeter. Calibration was undertaken before each test and was accomplished by applying a known deflection using a micrometer mounted above the transducer. A simple, direct conversion from transducer output to corner deflection was thus obtained. The maximum applied load was such that the corner deflection did not exceed 1mm (i.e. half the plate thickness). Before testing, a load greater than this maximum was applied to ensure that any deformation at the corner during test was minimised. Checks were made to confirm that no detectable specimen movement took place at the 'fixed' corners. The tests were repeated three times on each plate and the modulus calculated from the average load/deflection gradient.

Since incremental dead weight loading was used, it was necessary to take 5 second isochronous readings to eliminate creep effects. It may be noted that a useful plate twist rig has been described by Konstantinov and Strelyaev[40] which can be used between the compression platens of a universal test machine.

4.3   Rail

The square plate used in the plate twist test was again employed in the arrangement shown in Fig.10a. Application of a compressive load P between points A and B induces a shear stress in the specimen. If the angle θ is made small the shear stress is given simply by

$$\tau = \frac{P}{\ell t}$$

where ℓ is the plate length and t the thickness.

Whilst this test has been widely used[23,28,41-45] it has been subject to criticism from a classical mechanics viewpoint due to the existence of free edges causing non-uniformity in the stress distribution. A detailed Fourier series analysis of symmetrically laminated orthotropic plates by Whitney *et al.*[28] has shown that in specimens of high aspect ratio ($\ell/b \geqslant 10$, Fig.10a) a uniform stress is found over most of the specimen for all except $\pm 45^{o}$ angle-ply laminates. The analysis also showed that in such a specimen considerable forces perpendicular to the rails occur at the corners CDEF of the test area. For the 0° case, with the fibres aligned parallel to the side supports, the transverse tensile forces are likely to exceed the strength of the material before the ultimate shear strength of the material is reached. With the fibres aligned at 90° the stress is more uniform over the whole area and the stresses perpendicular to the rails are of little importance relative to the longitudinal strength of the composite. For this reason, most of the tests were conducted with the fibre axes perpendicular to the rails, but a few 0° tests were undertaken to determine the importance of fibre orientation in practice. The stress mode in this case is 'longitudinal' shear.

The experimental arrangement, a simplified version of that used by Boller[41], is shown in Fig.10b. The side supports were of ground mild steel with hardened, square section tips at the points labelled T . The surfaces in contact with the specimen were lined with grade 600 emery paper. Six clearance holes were drilled in the specimen and the clamping bolts tightened to a torque of 25N m. For the high strength material it was not possible to sustain sufficient stress using emery paper and so metal side plates were bonded to the CFRP specimens: load was applied via the bolts to the side plates. By testing a specimen in which the side plates fitted exactly in the rails and using clamps it was possible to fail a specimen without drilling holes in it. In this way it was shown that the bolt holes in the standard specimens did not affect the maximum sustainable shear stress in the CFRP specimen. One strain gauge was bonded to the centre of each side of the specimen at 45° to the fibre axis thus allowing the effect any bending of the specimen to be accounted for. The specimen was tested to failure between the compression plattens of a universal testing machine at a head displacement rate of 1mm/min. Aluminium alloy plates between the tips T and the

platens allowed some bedding-in to take place and thus alleviated the effects of any slight misalignment. The strain versus load to failure was automatically recorded using strain gauges and an electrical load transducer.

Sims[43] describes a 'balanced' rail shear technique in which two identical laminate areas are tested in parallel. Whilst it was considered that the extra complexity involved in this technique was not justified for flat laminates, a modified version employing small cubes of unidirectional CFRP was used to determine the relative shear moduli in the three principal planes.

The test configuration is illustrated in Fig.11. Three aluminium alloy side plates were bonded to the two 10mm cubes of CFRP as shown. A pair of strain gauges was attached to each block. Load was applied between the compression platens of an Instron test machine, the roller being inserted as shown to minimise the effects of any slight misalignment of the side plates. Load-strain curves, up to a maximum stress of $0.5MN/m^2$, were recorded automatically. The test was carried out three times with the fibre axes in each of the three principal planes. Similar tests were carried out on resin blocks of the same size.

4.4   Short beam

This well known method[5,46], illustrated in Fig.12 is based on the fact that in some cases, a beam loaded in three-point flexure may be made to fail in 'interlaminar' shear at the neutral plane before the outer fibres break in tension or compression. A number of investigations[29-31,47,48] of the effect of specimen geometry on the measured strength have been made and for CFRP the recommended[5] span/thickness ratio is five, but even at this ratio composites of low fibre strength or high interlaminar shear strength may fail prematurely in flexure[49,50].

Whilst this test is economical of material and simple to perform there is a number of drawbacks. The principal drawbacks are that the stresses are non-uniform, even in the plane of the laminate, that states of combined stress exist and that severe stress concentrations arise at the points of load application[29-31,49]. Classical beam theory gives the relationship for shear stress τ as

$$\tau = \frac{3}{4} \frac{P}{bt} \tag{4}$$

where P is the applied load
and   b and t are the width and thickness respectively.

However, it has been shown[29,31] that the assumptions on which this theory is based do not pertain to the short beam test. A finite element analysis by Berg[29] has shown that due to stress concentrations in the region of the loading points, the maximum shear stress does not occur at the centre of the beam and that the method may significantly underestimate the true maximum shear strength. Similar conclusions have been reached by Sattar and Kellogg[31] using a distortion energy failure criterion and an exact theory of elasticity solution, although the predicted reduction in measured strength for the RAE specimen in this case is only about 8%. However, even this theory is inadequate[51] since it assumes there are no end effects (τ must be zero at the ends); also equation (4) assumes a linearly elastic stress-strain relationship which is in general not true. As previously noted[11], the measured shear properties are also dependent on the rate of loading. In this particular test the measured strength has been shown[52,53] to drop with very rapid loading and it is thought that this results from the fact that the stress concentrations discussed above do not have time to dissipate plastically.

Despite these drawbacks it is a simple, reproducible test, useful for qualitative evaluation and likely to provide a satisfactorily accurate measurement of 'interlaminar' shear strength.

The method has been adequately described elsewhere[5,46] and the dimensions are given in Fig.12. The specimens were tested to failure in the Instron universal machine at a head displacement rate of 5mm/min (see Ref.11).

4.5 Transverse compression

Rosen and Dow[54] suggested that a block compression test of unidirectional material transverse to the filaments would yield more representative quantitative values for shear strengths than short beam tests. As previously noted, the presence of transverse compressive forces has been shown[1] to significantly increase the measured composite shear strength in the (2,3) plane (see Fig.3). However, since the test is so simple and economical of material it was considered worthwhile examining, since at least it would give an upper limit to the value of shear strength, albeit in the 'transverse mode'. The specimens were approximately 5 × 3 × 2mm (see Fig.5) and were tested between the compression platens of a universal test machine.

4.6 Thin-walled tubes

It is generally accepted that, from the applied mechanics aspect, the use of thin-walled tubes provides not only the most satisfactory method of determining

the 'in-plane' shear properties but also a specimen configuration suitable for general composite materials characterisation. If the ratio of tube radius to wall thickness is sufficiently large and one end of the tube is free to move in the direction of the tube axis as well as rotate, a reasonably pure state of shear stress has been shown to exist[15,32,33,55]. One disadvantage is that the modulus is a function of the fourth power of the internal and external tube diameters (see equation (5) following), so that care in tube manufacture and measurement is necessary. Many workers have used filament wound tubes since the constraining end-attachment effects on strength discussed earlier (section 2.2) do not arise, but such a method of manufacture is unlikely to produce results representative of the properties of flat laminates fabricated from resin preimpregnated sheet. It was therefore necessary, as shown in the subsequent description of specimen manufacture, to use tubes with the fibres aligned parallel to the tube axis as the nearest approximation.

The dimensions of the tube are given in Fig.13; the thickness to radius ratio of 1:12.5 is subsequently shown experimentally to be adequate. With rigid end fixings Rizzo and Vicario[56] have shown theoretically that serious stress concentrations may arise in the region of the end attachments. In an endeavour to alleviate this problem the use of epoxy end fittings to allow some deformation to occur within the gripped length was investigated. The design of the end fitting is shown in Fig.13 and consists of 25mm thick, 90mm diameter epoxy* blocks together with a 2.5mm thick aluminium alloy facing plate. The end was cast with 12.5mm of the tube within the block. This allowed sufficient shear transfer area from the block to the tube and the metal plate distributed the load uniformly from the attachment bolts. A long (300mm) CFRP tube of similar cross section was fabricated and strain gauged at intervals between the centre and one end. Epoxy end fittings were cast on and the initial modulus measured at each gauge position and acceptable agreement between gauges obtained. The length of the tube was then reduced in stages so that the end gauge lay first close to the end fitting and was then embedded in the epoxy. The moduli at the exposed gauge positions did not change significantly and the strain registered by the embedded gauge was reduced to approximately 15% of the exposed gauges. It was thus apparent that some shear strain was able to occur within the embedded region and that this rose to the test section value without significant stress concentrations. This also resulted in a tube length considerably shorter than that considered necessary by Pagano and Whitney[55].

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* CIBA HY753/HY951 (10% by volume).

The final design assembled in the test rig is shown in Fig.14a and b. A tensile load applied to the rig by the Instron universal testing machine was converted by the lever system to a pure torque. The tube end to which the moment was applied was also free to move axially and so allowed the small amount of longitudinal contraction which takes place to occur unhindered. To ensure that the rig was inducing no bending, one tube was tested with six strain gauges located round the central circumference: no detectable difference in strain was observed. A similar exercise with internal and external gauges showed no measurable strain gradient through the wall thickness.

The strain from a pair of diametrically opposite 45° gauges was automatically recorded by the servo chart drive system as the specimen was loaded to failure, the ultimate stress being reached within approximately 10 seconds. The shear stress τ_{12} was calculated from the expression

$$\tau_{12} = \frac{16 d_e}{\pi (d_e^4 - d_i^4)} \times \text{torque} \qquad (5)$$

where d_e and d_i are the external and internal diameters respectively.

5 SPECIMEN MANUFACTURE

5.1 Materials

In order to eliminate batch to batch variations it was important that the same batches of resin impregnated carbon fibre sheet were used for all the tests. The actual material used in the programme was governed by the fact that it was the only material available at the time. The material properties are listed in Table 2. The sheets supplied were approximately 1m long in the direction of the fibres, 0.3m wide, 0.25mm thick and contained about equal parts by weight of fibre and resin.

5.2 Unidirectional flat laminates

The sheets were press-moulded to produce boards 200mm long (in the fibre direction), 90mm wide and about 2mm thick. The fibre volume fraction of the prepared boards was varied between 0.45 and 0.7 by increasing the number of plies and the applied pressure. The laminate was inserted in a press, preheated to 160°C and the pressure increased in stages. After moulding the board was post cured in an air-circulating oven at 160°C. The boards were ground flat and to a uniform thickness; two 70mm square and several 12.5 × 10 and 5 × 3mm specimens were cut from each board and the edges ground smooth and square. The square

plates were used first for the plate twist tests. They were then drilled, as in Fig.15, and tested to failure in the rail shear rig. Since it may be anticipated that peak stresses will arise near the free ends of short beam specimens[29], care was taken to minimise local stress concentrations by grinding smooth the cut faces.

A number of 2mm thick type II fibre and 10mm thick type I fibre specimens were fabricated by an autoclave process[57]. The material properties are listed in Table 2 and the specimens identified throughout the report by the prefixes AC .

5.3 Thin-walled tubes

For many torsion tests on thin-walled tubes the method of fabrication is that of filament winding. However, such a method is unlikely to produce composites whose properties reflect those of flat laminates. It was therefore necessary to fabricate the tubes from the same batch of sheets as the flat laminates. A tube with circumferential fibres fabricated from sheet would obviously have a dis-continuity on the inner and outer surfaces. The effect of these discontinuities could be reduced by using a large number of plies but this would necessitate a relatively large diameter and an increase in material cost. In addition, laminat-ing pressure applied either externally on to a male former or internally into a female former had been found in preliminary investigations to produce poor quality tubes. In neither case are the fibres able to move radially; in the first case compaction results in misaligned fibres, while in the second case the fibre volume fraction varies from high (with associated resin starvation) at the inner surface to low at the outer surface. Only by elaborate heating and pressuriza-tion at the time of winding could a reasonable composite be obtained. It was therefore evident that the fibres would have to run parallel to the tube axis and it was considered that high quality tubes could be obtained more readily by expanding a metal mandrel into a metal cylinder than by the male mould/external pressure technique. Further, fabrication by hot moulding around a fixed male mandrel[33] results frequently in cracking of the laminate due to resin contraction during cooling. The moulding rig used in this programme is illustrated in Figs.16 and 17. The eight-segment mandrel is covered with rubber tube and, by simultane-ously screwing bolts A and B, the tapered rods C and D expand the mandrel within the outer tube. This tube is accurately positioned by blocks E and F, the tapered rods making a sliding fit in the blocks so that the expanding mandrel remains concentric with the mould tube throughout expansion of the mandrel. The blocks were drilled as at G to allow excess resin to exude. By variation of the wall thickness of the outer metal tube, the thickness of the CFRP tube may be altered.

The resin preimpregnated carbon fibre sheet was cut to the appropriate size and the plies laid up in a stepped manner. The size of the steps, which allowed the material to be wrapped around the unexpanded mandrel without overlap, was determined empirically. The rubber covering of the mandrel was coated with release spray, the plies wrapped around the mandrel and inserted, together with an outer layer of release paper, into the outer metal tube. The tube was then located between the blocks and the tapered rods inserted until they just engaged in the mandrel. The whole rig was put into an air circulating oven at $120^{\circ}C$ until it reached a uniform temperature. Bolts A and B were then tightened until the mandrel was fully expanded and the laminate was finally replaced in the oven at $160^{\circ}C$ and allowed to cure for $1\frac{1}{2}$ hours.

The laminated CFRP tube was then supported with its axis accurately perpendicular to, and one end 15mm above the centre of, the base of a 90mm diameter open mould. A 2.5mm thick aluminium alloy plate was placed in the mould and epoxy resin poured in until the level reached 12.5mm up the CFRP tube. The resin was allowed to cure at room temperature and a similar epoxy fitting was cast on the other end of the tube. The end fittings were then drilled for attachment to the torsion rig.

The expression for the shear stress has been seen to be a function of the fourth power of the tube diameter and thus small uncertainties in measurement could introduce large errors in the stress, and hence in the calculated modulus. Because very small thickness variations inevitably occurred, the internal diameter was calculated after failure from the measured outside diameter and the volume (by Archimedes principle) of an exact length of tube. Since fabrication was costly compared to that of flat laminates, only tubes of a nominal 0.65 fibre volume fraction were prepared.

5.4 Fibre volume fraction and void content

The fibre volume fraction V_f and void content V_v of each specimen were determined from small samples of the tested specimens by a wet combustion and density column technique as described by Ewins and Childs[58].

6 THEORY

6.1 Prediction of shear modulus

A comprehensive review of the numerous approaches to the prediction of elastic constants of composite materials, including shear modulus, has been given by Ashton *et al.*[36] and will not be repeated here. Most of the solutions involve

extensive computational operations and are therefore unsuitable for 'desk' calculation. Using a finite difference method involving a doubly periodic rectangular fibre array Adams and Doner[59] have produced a solution which is in good agreement with published experimental data for both carbon and glass reinforced plastics[60,61].

The methods of Halpin and Tsai[14] and Hashin and Rosen[62] may however be reduced to simple forms. The Halpin-Tsai equation gives the relationship between composite and matrix shear modulus as

$$\frac{G_c}{G_m} = \frac{(1 + \delta \eta V_f)}{(1 - \eta V_f)}$$

(6)

where $\eta = \dfrac{\left(\dfrac{G_f}{G_m} - 1\right)}{\left(\dfrac{G_f}{G_m} + \delta\right)}$,

the reinforcement constant δ is assumed to be unity, and suffices c, f and m refer to the shear moduli of composite, fibre and matrix respectively.

If $G_f \gg G_m$ the expression reduces further to

$$\frac{G_c}{G_m} \simeq \frac{1 + V_f}{1 - V_f} \, .$$

(7)

The results of equation (6) give estimates of shear modulus which agree with experiment only up to fibre volume fractions of 0.5. In order to obtain a simple solution which approximates to the lengthy analysis of Adams and Doner[59], Hewitt and de Malherbe[63] have proposed, without theoretical justification, modifying the Halpin-Tsai equation so that

$$\delta = 1 + 40 V_f^{10} \, .$$

(8)

Sendeckyj[64,65] has produced an exact solution which, whilst it is complex for the general case, reduces to the following simple expression for a square array

$$\frac{G_c}{G_m} = \left[\frac{1 + 2A}{(1 - A)}\right] \left[1 + \frac{3A^2}{(1 - A)\left(\frac{\pi^2}{V_f^2} - A^2\right)}\right]$$

(9)

where $A = \eta V_f$

and $\delta = 1$.

Sendeckyj also shows that equation (9) gives results in excellent agreement with his more exact solution.   It may be noted that if only the first term in brackets is retained the expression becomes identical to equation (6).

The above equations all express the composite shear modulus in terms of the fibre and matrix shear moduli and the fibre volume fraction of the composite. Values of fibre volume fraction and matrix shear modulus may be readily obtained by experiment; although it has been suggested by Schrager and Carey[66] that, due to stress concentration effects, assuming the matrix modulus in the vicinity of the fibre to be that of the bulk material may be erroneous. Investigation of the micro-structure of carbon fibres has shown them[67-69] to be highly anisotropic with a radial variation of basal plane alignment which will almost certainly cause a corresponding variation in shear modulus. However, assuming the fibres to be transversely isotropic, Dean and Turner[70] have derived the elastic proper- ties of fibres in an epoxy matrix composite. Using an ultrasonic pulse trans- mission technique the composite moduli were determined for various fibre volume fractions. From the Halpin-Tsai equation (6) they were able to work back to an estimate of the fibre moduli. The longitudinal fibre shear moduli so obtained of between 14 and $26MN/m^2$ were similar to those assumed in previous analyses[59,64,71]. Heaton[71] and Whitney[72] have shown the calculated composite shear moduli to be significantly lower when fibre anisotropy is introduced. It is fortunate therefore that a reasonable estimate of the composite shear modulus is not dependent on an exact knowledge of the appropriate fibre modulus. For instance, using equation (6) a large error in fibre modulus assumption (say 20 instead of $30MN/m^2$) for a 0.6 fibre volume fraction composite using a typical resin $(G_m = 1MN/m^2)$ produces only a 5% change in composite modulus.

A comparison of the various methods for a typical carbon fibre/epoxy composite is given in Table 3 and Fig.18. It can be seen that the Hewitt and de Malherbe[63] empirical equation is in acceptable agreement with the analysis of Adams and Doner[59]. The equations of Halpin-Tsai[14] and Sendeckyj[64] produce significant underestimates of the shear moduli at fibre volume fractions above 0.5 and since CFRP is unlikely to find much application at fibre concentrations below 50%, these methods are of limited practical use. Using equations (6) and (8) the modulus variation with fibre volume fraction was calculated for two typical resins. The curves are plotted in Fig.19.

Since the composite shear properties are largely determined by the properties of the matrix it is to be expected that any variation of matrix shear modulus with void content would incur a corresponding variation in composite shear modulus. Jones and Noyes[73] summarize the various approaches to the prediction of the effect of voids on the matrix shear modulus. The following expression deduced analytically was selected by Jones and Noyes and provided best agreement with existing test data,

$$\frac{G_{mV}}{G_m} = \frac{1 - \rho}{1 + \rho b}$$ (10)

where $b = \frac{2(4 - 5\mu)}{7 - 5\mu}$

ρ is the matrix void volume fraction

and μ is Poisson's ratio (assumed here to be 0.3).

The above equations lead to the prediction that for an epoxy-matrix composite of 0.5 fibre volume fraction containing a composite void content of 1% (i.e. $\rho = \pm 0.02$ and $b \simeq 0.91$) the matrix modulus will be reduced by about 4% causing a similar reduction in composite shear modulus.

6.2 Prediction of shear strength

Although an improved understanding of basic failure mechanisms has been obtained from a number of analyses (see, for example, Ref.74), the reliable prediction of ultimate shear strength from the constituent material properties has yet to be accomplished. The three basic parameters affecting the shear strength of a high quality unidirectional composite are the ultimate shear stresses sustainable in the fibre, in the matrix and at the interface. Hashin[75] suggests that a lower bound for a void free, well-bonded composite is the shear strength of the matrix (τ_m). An upper limit of $4/\pi \times \tau_m$, as $V_f \rightarrow 1$ has been proposed by Shu and Rosen[76]. Using the hypothesis that the shear strength is limited by the allowable matrix shear strain, Chamis[77] has derived the following semi-empirical relationship for shear strength:

$$\tau_c = \frac{\beta_s \hat{\phi}_m G_c}{\beta_v} \left\{ 1 - \left(1 - \frac{G_m}{G_f}\right) \sqrt{\frac{4(1 - V_v)}{\pi}} \right\}$$ (11)

$$\beta_v = \cfrac{1}{1 - \sqrt{\cfrac{4V_v}{\pi(1 - V_f)}}} \qquad \text{(void correction)} \quad .$$

Assuming the variables such as void size and distribution, filament spacing and uniformity, interface bond strength, and residual stresses are approximately invariant for a particular fabrication process, he suggests all these may be grouped into a theory/experiment correlation factor β_s . $\hat{\phi}_m$ is the limiting matrix shear strain. For a void free, well laminated composite the theory-experiment correlation coefficients β_s and β_v approach unity. For the case where the fibre interface is the weakest link, Noyes and Jones[78] have suggested a semi-empirical formula of the form

$$\tau_c = \frac{\tau_m}{(1 + V_f)^2} \qquad (12)$$

where τ_c and τ_m are the shear strength of the composite and matrix respectively.

A number of investigations has been undertaken to determine the magnitude of the stress concentrations in a matrix caused by the presence of the fibres[59,64,65,79]. The stress in all these cases is a maximum at the points on the fibre/matrix interface closest to adjacent fibres. The results of Adams and Doner[59] (which are similar to those of other workers) are given in Fig.20 for a square array with $G_f/G_m = 20$. It can be seen that at higher fibre volume fractions approaching 0.7 the stress concentration factor rises rapidly. Reynolds and Hancox[80] have investigated the relationship between composite shear strength and fibre/matrix bond strength in terms of fracture mechanics theory. Their experimental results and empirically determined stress concentration factors confirm the trend predicted by Adams and Doner[59].

From the above considerations it is possible to predict that for a composite in which the interfacial bond strength exceeds the yield strength of the matrix, the composite shear strength will fall by up to 50% as the fibre volume fraction, V_f , is increased from 0 to 0.65 (see Fig.20). As V_f approaches 0.7 the rapid increase in stress concentration factor will cause a corresponding fall in shear strength. For composites with a bond strength weaker than the matrix the reduction in strength with increase in fibre volume fraction is likely to be more rapid. Scanning electron micrographs of fractured shear specimens by Novak[81]

tend to confirm these predictions and also to indicate that the way in which the crack propagates in composites of increasing strength produces increasingly brittle failures.

Noyes and Jones[78] have also investigated the effect of voids and derived the following expression

$$\frac{\tau_v}{\tau_m} = \frac{1}{(1 + V_f)^2} \left[1 - \frac{B\rho}{1 + \rho(B - 1)} \right] \qquad (13)$$

where τ_v is the shear strength of the voidy composite

ρ is the void volume fraction in the matrix

and B is an empirical constant.

For the case of spherical voids in a cubic array, Greszczuk[82] has derived the following equation for the ratio of voided to unvoided shear strength:

$$\frac{\tau_v}{\tau} = 1 - \frac{\pi}{4} \left[\frac{6V_v}{\pi(1 - V_f)} \right]^{\frac{2}{3}} . \qquad (14)$$

Experiments for glass/epoxy composites were said to be in good agreement with the theory over a wide range (0-23%) of void contents. Other empirical equations have been derived by Brelant[83], Hand[84] and Kohn *et al.*[85].

The variations of shear strength with void content predicted by Chamis, Noyes and Jones (assuming arbitrarily B = 12) and Greszczuk are plotted in Fig.21. Also plotted are experimental results by Stone and Clarke[86] for a high shear modulus and strength carbon/epoxy composite.

7   RESULTS AND DISCUSSION

7.1   Fabrication techniques

At the beginning of the experimental programme described in this Report the then current method of laminate production was by press-moulding. It will be seen in the following sections that this technique sometimes produced laminates with high void content (up to 12%) and mechanical properties which varied significantly between nominally identical specimens. In addition, the shear stress-strain relationship showed considerable nonlinearity throughout the stress range and high strain to failure. These factors have a particularly marked effect on the measurements of shear strength and its variation with volume fraction (section 7.3).

For this reason a limited number of laminates were subsequently prepared using the autoclave process[57], providing specimens of uniform high quality and low void content ($V_v < 0.5\%$). A limited range of fibre volume fractions is obtainable using this process and hence measurement of the variation of shear modulus and strength with fibre volume fraction was not undertaken on the autoclave material.

7.2   Modulus measurement and prediction

The results are presented in Figs.22 to 30 where, for clarity, only the mean figures for bands of fibre volume fraction $V_f \pm 0.25$ are shown. The curves represent the predicted modulus for void-free specimens derived from equation (8) (section 6.1). Typical stress-strain curves for the rail and tube tests are shown in Figs.27 and 28.

Considerable scatter in the measured modulus is evident, particularly in the type I composites. However, by comparing the results for the plate twist and rail tests, Figs.22 to 25, it can be seen that in general the results are similar and hence the scatter is a reflection of the variation of material properties and not of the method of test. It can be seen that most of the modulus variations occur above the predicted values and these higher stiffnesses obtained by experiment may be due to the presence of a considerable proportion of misaligned fibres (section 3.3). The greater variability of the type I fibre composites may be attributed to the poorer quality of the laminates which have an average void content (6.3%) twice that of the type II material. The laminates for both type I and type II composites were prepared by the same standard press-moulding technique and the difference in quality may be due to the facts that with type I material, fibre breakage during fabrication and fibre 'springback' after lamination are more likely. Some scatter may also arise with both types of fibre composite due to the difficulty in obtaining precise measurements of fibre volume fraction and void content.

The differences between the plate twist, rail and tube modulus measurements are in general small and random - some variation between methods is likely to arise from the different shear modes and fabrication techniques involved. Of the rail results it may be noted that the 0° measurements are slightly higher than those taken at 90°. It is thought that this is a reflection of the difference in stress distribution between the two methods (section 4.3). Referring to the results of the 90° rail measurements on type II laminates which show least scatter (replotted for clarity as Fig.29) it may be seen that the agreement between

experiment and theory is good up to 0.65 volume fraction. The lower measured modulus at fibre volume fractions approaching 0.7 may be the result of the stress concentration factors discussed in section 6.2 and the larger significance of voids at high fibre volume fractions.

The magnitude of the void content corrections (section 6.1, equation (10)) is obviously too great. The analysis underlying equation (10) was based on an assumption of a regular cubic array of spherical voids within the composite. Microscopic examination of the materials shows that in material with void content greater than 1.5% (section 7.2) the majority of voids occur as large inclusions between laminae (see Fig.32). Voids such as these would be expected to have a much smaller effect on the longitudinal shear modulus than on the interlaminar shear stiffness.

The relative shear stiffnesses in the three principal directions are shown in Fig.30 for the AC type I fibre composites and it can be seen that all the moduli, including that of the resin, are less than expected. This is thought to be the result of the non-uniformity of shear strain across the very small test area, the strain being measured over an area subject to above-average shear stress. However, it is unlikely that such an effect would greatly alter the relationship between stiffnesses. For the volume fractions tested the longi-tudinal, interlaminar, transverse and resin shear moduli are in the ratios 1:0.85:0.42:0.25 respectively.

7.3 Strength measurement and prediction

The strengths are plotted as a function of fibre volume fraction in Figs.33 to 38 and as a function of void content in Figs.39 to 44. The individual strength measurements of the 90° rail tests are given but for the short beam and transverse compression tests each point is the mean of six and two tests respectively. Results of 0° rail tests are given in Fig.36 for comparison. In an attempt to separate the effects of fibre volume fraction and void content on strength, both relationships were assumed to be linear up to 0.68 fibre volume fraction and a partial regression analysis was performed for fibre volume frac-tions below 0.68, the results being shown as solid lines in Figs.39 to 44. The results above $V_f = 0.68$, were however omitted from the regression analysis since stress concentration effects caused the measured strengths to depart rapidly from the general trend (see Fig.20). In Figs.33 to 38 the variation of strength with fibre volume fraction is given for average and zero void contents and in Figs.39 to 44 are given the variation of strength with void content for a fibre

volume fraction of 0.6. In every case the strength increases with increase in volume fraction (up to 0.68) - the opposite trend to that predicted (see section 6.2). Microscopic examination of failed specimens showed large deformation to have occurred in resin-rich areas, indicating considerable plastic flow in the matrix; this fact is reflected in the low composite yield stresses and high strains to failure.

It must therefore be concluded that the matrix showed considerable non-linearity in its stress-strain behaviour at stresses well below the interfacial bond strength. Under these conditions the variation of stress concentration factor with volume fraction is likely to be closer to unity than that shown in Fig.20 for fibre volume fractions below about 0.65; the high void content would reduce the shear strength at all fibre volume fractions. The presence of increasing amounts of fibre might therefore produce an increase in strength as predicted by Shu and Rosen[76] (see section 6.2); enhanced by the large proportion of misaligned fibres (Fig.31). The results from these press-moulded specimens serve to accentuate, and therefore highlight, the differences in the strengths, and the different shear modes, obtained from the various test methods. Fig.45 compares the variation of shear strength with fibre volume fraction of type II composites ($V_V = 0$) as determined by the several techniques. This variation between techniques may well be attributed to the difference in boundary conditions discussed in section 2. The short beam test, with no constraint on shear deflection and significant stress concentrations, provides a lower limit on the shear strength. The uniformly stressed tubes, with little restraint from the end fittings show a somewhat greater failing stress. A crack initiating in the tube test section may progress catastrophically along the length of the tube, due to the comparatively low stiffness and strength of the epoxy end fittings. Examination of the failed tubes showed that in every case both end fittings failed at the line of the tube failure. If the stress/strain curves to failure for tube and $90°$ rail tests are compared (Figs.27, 28) it will be seen that not only is the measured rail strength higher but the strain to failure is also greater. This may be a direct reflection of the rigid constraint imposed along the edge of the specimen. A similar argument, together with the increased significance of stress concentrations, would account for the lower strength determined by the $0°$ rail test, Fig.36. The high shear strengths derived from the transverse compressive test were expected due to the effect of transverse forces on the shear strength[1].

The results of the tests on high quality autoclave specimens are shown in Fig.45 and are the means of six tests each. The discrepancies between the strengths measured by the three methods may be in part due to the relative size of the test specimens in that larger specimens are more likely to contain an area of reduced strength. This concept is supported by the larger scatter evident within a given laminate in the strengths measured by the transverse compression tests. The slight shear stress concentration (SCF $\simeq$ 1.1, Ref.28) near the free edges of 90° rail specimens may account for the somewhat lower strengths measured by the rail test.

Comparing the effect of voids on the composite shear strength determined experimentally with the theoretical analyses (Fig.21) it is evident that for the low strength composites, as with the modulus variation, the measured reduction is less than predicted. Little significance is attached to this in view of the poor strength of these composites. The more evenly distributed voids observed by Lenoe[87,88] and Kohn et al.[85] had an effect approximately that predicted by Greszczuk[82].

The tests on high quality, high strength composites by Stone and Clarke[86] show that up to void contents of about 1% the reduction in shear strength due to voids is somewhat less than that predicted (see Fig.21). At low void contents ($<$ 0.5%) there is considerable experimental scatter due to the difficulty in obtaining void content measurements of sufficient accuracy, while other parameters such as fibre misalignment have greater significance. As the void content increases beyond 0.5%, their presence becomes increasingly important until at 2% the strength has dropped by 35% - about twice the fall predicted by Chamis[77] and Greszczuk[82]. Above 2% the fall in strength becomes less rapid.

Microscopic examination shows that up to 1.5% void content the voids are generally small and randomly distributed such as would be caused by trapped volatiles. Above 1.5%, larger voids occur between laminae and are usually formed by air trapped adjacent to misaligned fibres on the surface of a laminae and not removed during the cure cycle. These large voids may cause a drastic reduction in interlaminar shear strength. It will be evident that the strength of a short beam specimen containing one relatively large interlaminar void will not be greatly reduced by the presence of a second void between a different pair of laminae. Hence the rate of reduction in strength might be expected to decrease above about 2% void content.

8 RECOMMENDATIONS

8.1 Modulus measurement

As far as measurement accuracy is concerned there is little to choose between the plate twist, rail and tube tests. Within the deflection constraints of the method, the plate twist test is simple and does not necessitate individual strain transducers for each specimen; but the laminates must be flat and the thickness uniform and accurately known. It should also be remembered that the shear mode in the plate twist test is 'transverse rotational' and not 'longitudinal'. Both rail and tube tests give accurate assessments of longitudinal shear moduli but in general require strain measuring equipment. Where a knowledge of the 'interlaminar' or 'transverse' modulus is required the modified rail test on thick laminates (section 4.3) may be employed. If the 'longitudinal' shear modulus is accurately known (e.g. from the standard rail test) and is also determined using the modified technique, allowance may be made for any underestimation of the interlaminar and transverse moduli (section 7.1).

The viscoelastic nature of epoxy matrix composites (section 2.4) must be emphasised, particularly when determining the modulus to failure which should occur within 6 seconds of the commencement of loading.

8.2 Strength measurement

It has been shown (section 2) that not only is the measured shear strength of a particular type of composite dependent on the shear stress mode and its uniformity but also, for low modulus materials, on the amount of edge constraint applied. The tube technique as described in this Report probably gives the most accurate estimate of shear strength and is particularly recommended for low modulus materials. However, it is an expensive technique relative to the others described and where the longitudinal shear modulus to failure is required the rail test has been shown to be a suitable alternative. Short beam and transverse compression tests will give simple and reliable estimates of the 'interlaminar' and 'transverse' composite shear strengths if carried out correctly. The transverse compression test is also useful for composites whose shear strengths are very high and which do not fail in shear under short beam test conditions.

8.3 Theoretical predictions

The predicted shear modulus using equation (8) (section 6.1) agrees well with the experimental results presented in this Report and elsewhere and may be used for most unidirectional carbon fibre composites that may be envisaged. In

addition, it is worth noting that the simple expression of equation (7) gives results of sufficient accuracy for many purposes.

Further investigation is necessary before the prediction of shear strength from the constituent material properties is possible. The knowledge to date highlights the importance of the matrix and fibre/matrix interface properties. The methods for predicting the effect of voids on the shear properties are also not yet sufficiently accurate to recommend their use.

Acknowledgments

Table 1

SUMMARY OF SHEAR TEST TECHNIQUES

Specimen configuration	Test nomenclature	Figure	Shear mode	Suitability for strength (S) or modulus (M)	Remarks	References
Thin beam	Short beam	5b	Interlaminar	S	Stress concentrations. non-uniform distribution, combined stresses	5,25,29-31,38,45-54,89-95
	Beam twist	5c	Transverse*	S(?), M	Non-uniform distribution of stress	16,96
	Off-axis tension	5d	Longitudinal	S(?),M	Combined stresses	6,12-22,97-100
	Beam resonance	-	Interlaminar or transverse*	M	Test facility not generally available	60,94,101-103
	Transverse compression	5a	Transverse	S	Combined stress	54
Thin plate	Plate twist	Similar to 5c	Transverse*	M	Limited to very small deflections	16,25-27,32,39,91,93-95
	Picture frame	5e	Longitudinal	S, M	Stress concentrations. Buckling likely	16,23-25,93,105
	Rail	5f	Longitudinal	S, M	Stress concentrations important in 0° case. Load attachment effects	23,28,41-45
Thick beam	Notch compression and tension	6a	Interlaminar	S	Stress concentrations. Non-uniform distribution	25,45,47,92,105-107
	Slip-plane	6b	Interlaminar	S	Stress concentrations. Non-uniform distribution	45
	I beam	6d	Interlaminar	S	Stress concentrations. Non-uniform distribution	25,95,108
	Punch	6c	Interlaminar or transverse	S	Stress concentrations	
	Acoustic	-	All three	M	Test facility not generally available	70,109,110
Wound or cylindrical	Split ring	7a	Transverse*	S, M	Combined stresses. Non-uniform distribution. Need to know Young's modulus	97,111
	NOL ring	Similar to 5b	Interlaminar	S	Stress concentrations. Non-uniform distribution	25,89,95,108
	Thin-walled tube	7b	Longitudinal	S, M	Load attachment effects	15,25,32,33,42,54-56,89, 93,95,105,112-115
	Rod	Similar to 7b	Longitudinal	S(?), M	Non-uniform distribution	9,25,32,61,80,92
Crossply	±45° tension	Similar to 5d	Longitudinal	S(?), M	Combined stresses. Boundary errors	35,43,98,116
	±45° + honeycomb sandwich	7c	Longitudinal	S(?), M	Stress concentrations	35,93,117
	0 + 90° disc	7d	Interlaminar	S	Non-uniform distribution	93

*Since the fibre axes rotate relatively, this is a rotational transverse stress and the measured moduli are closer to true longitudinal than transverse

Table 2

RESIN PROPERTIES OF IMPREGNATED CARBON FIBRE SHEET

	Density	Young's modulus GN/m^2
Type I composite	1.20	3.0
Type II composite	1.20	3.0
AC Type I composite	1.21	3.4
AC Type II composite	1.25	5.6

The resin shear modulus was taken to be $E/2.6$

Table 3

THEORETICAL PREDICTIONS OF SHEAR MODULUS FOR $G_f/G_m = 20$

Composite modulus ÷ matrix modulus (G_c/G_m)					
V_f	Adams and Doner square array	Hewitt and Melharbe	Halpin-Tsai	$\dfrac{1 + V_f}{1 - V_f}$	Sendeckyj square array
0.04	1.24	1.07	1.07	1.08	1.08
0.40	2.26	2.14	2.13	2.33	2.15
0.55	3.18	3.06	2.98	3.44	3.07
0.70	5.44	5.81	4.45	5.67	5.03
0.75	7.74	7.74	5.22	7.00	6.30
0.78	9.80	9.31	5.80	8.09	7.36
AC 0.60	-	7.73	-	-	-

SYMBOLS

A	defined in equation (9)
B	empirical constant
G	shear modulus
P	applied load
V	volume fraction
b	specimen width
d	specimen diameter
ℓ	specimen length
n	number of elements
t	specimen thickness
x	dimensional change
β	theory/experiment correlation coefficient
δ	reinforcement constant
η	defined in equation (6)
θ	angle between load and specimen axes
μ	Poisson's ratio
ρ	volume fraction of voids in matrix
σ	uniaxial stress
τ	shear stress
ϕ	shear strain

Suffices

1, 2, 3	in directions or planes defined by 1, 2, 3, see Fig.2
i, e	internal, external
c, f, m, v	of composite, fibre, matrix, voids
s	for particular fabrication process

at failure

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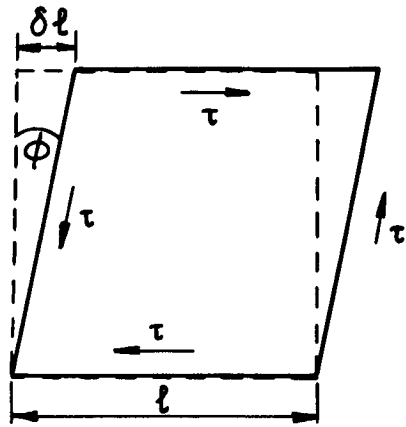
Fig.1   Plane shear stress and strain

Fig.2   Laminate axes

Interlaminar τ_{13}

Transverse τ_{23}

Longitudinal (in-plane) τ_{12}

3

(Plane of laminae)

1

2

(Fibre direction)
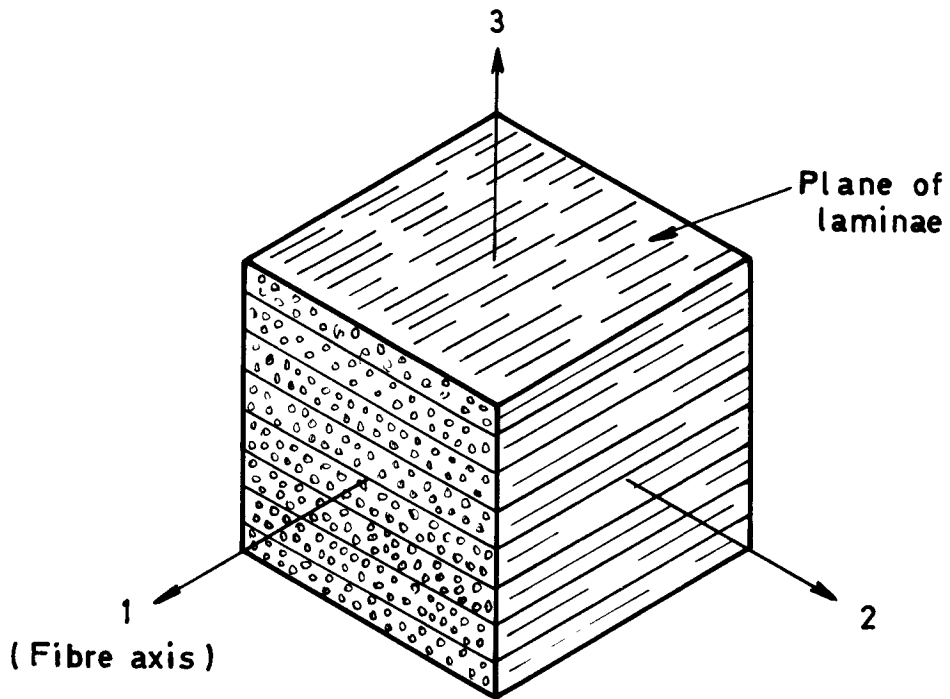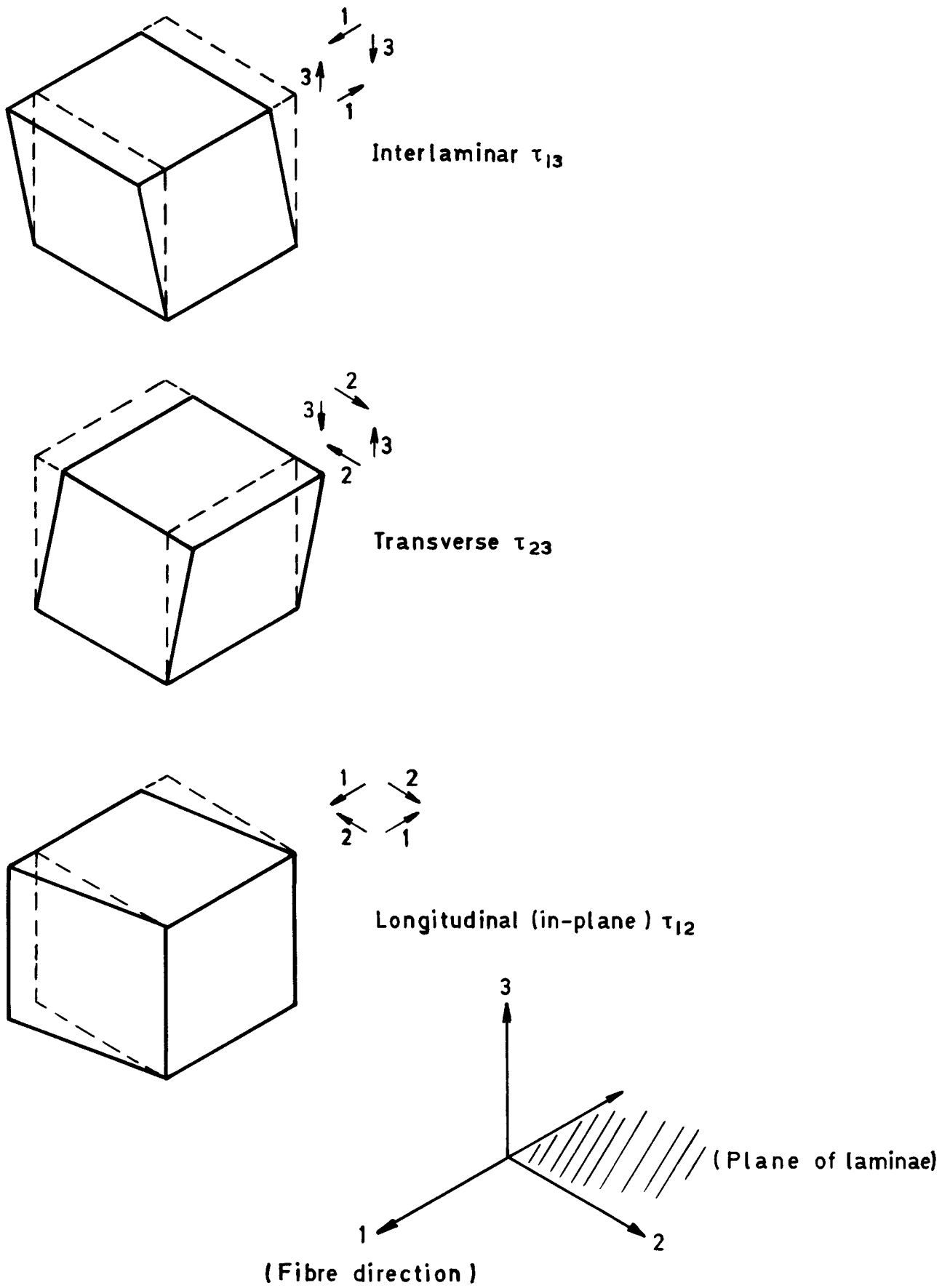
Fig.3   Definition of shear planes
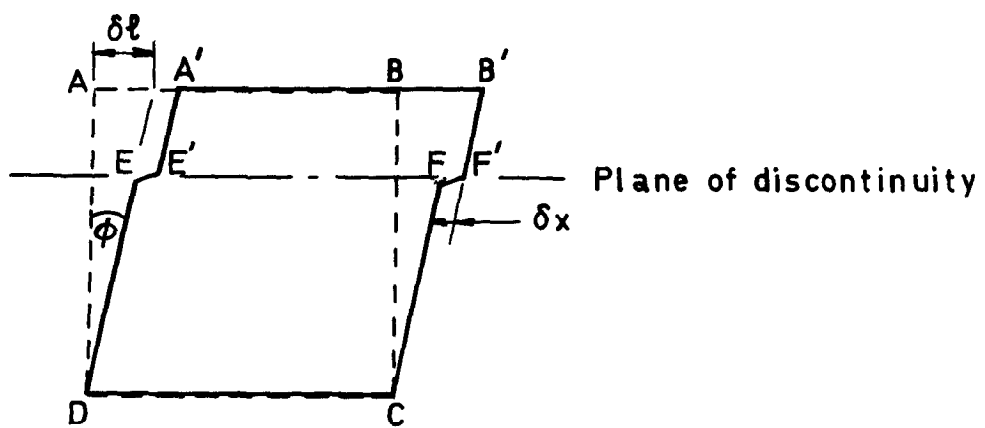
Fig.4   Shear along a discontinuity

a Transverse
compression

b Short beam

c Beam twist

d Off-axis tension

e Picture frame

f Rail
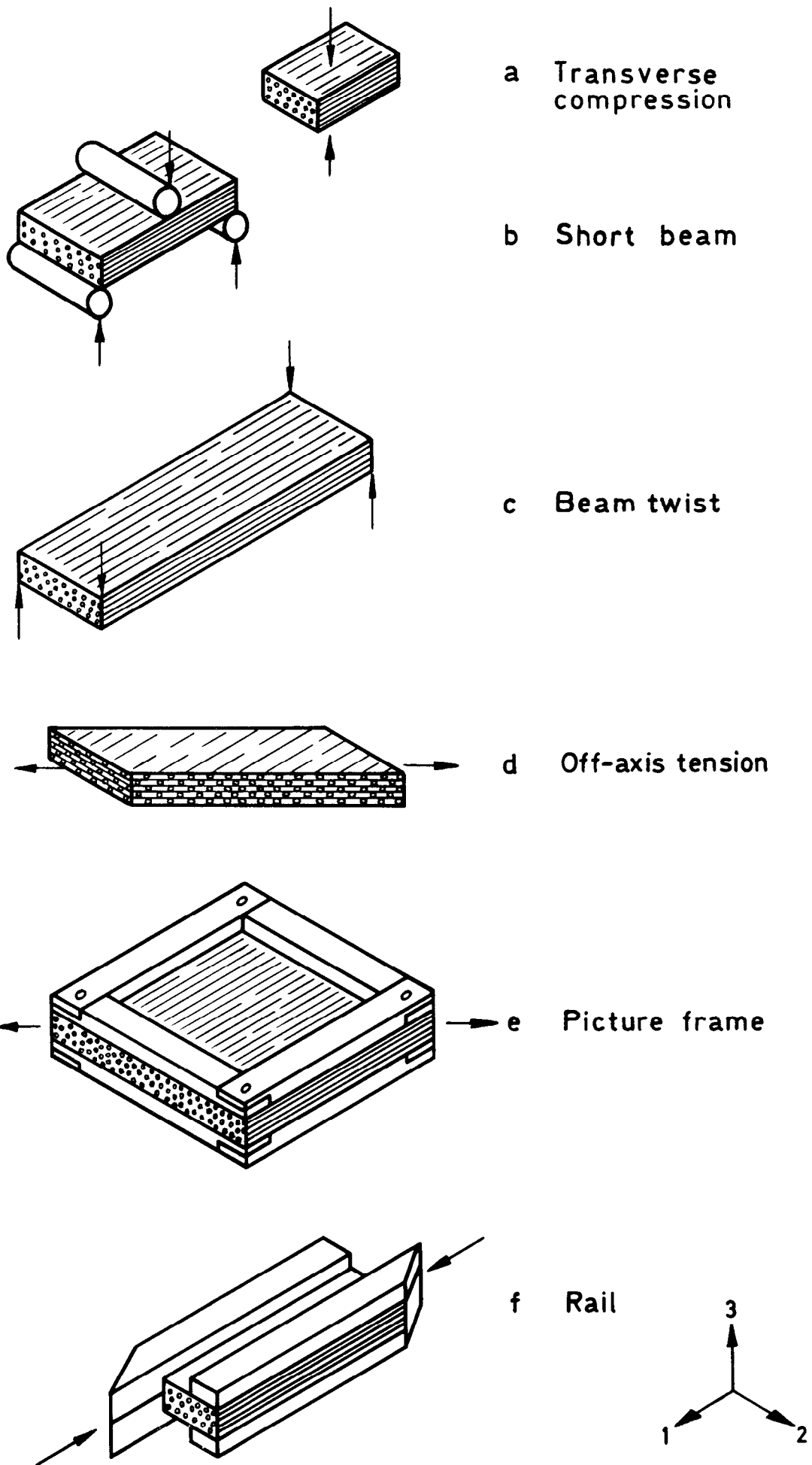
Fig.5a-f   Shear tests for thin beams
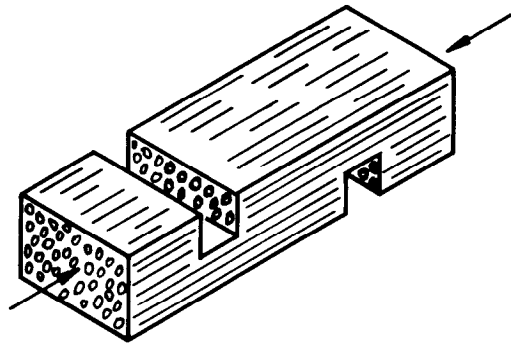
a   Notch

b   Slip-plane

Release
film
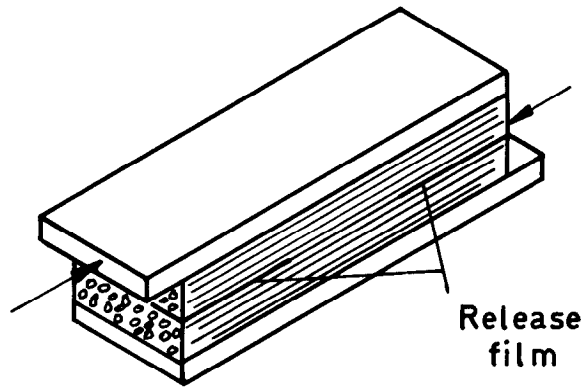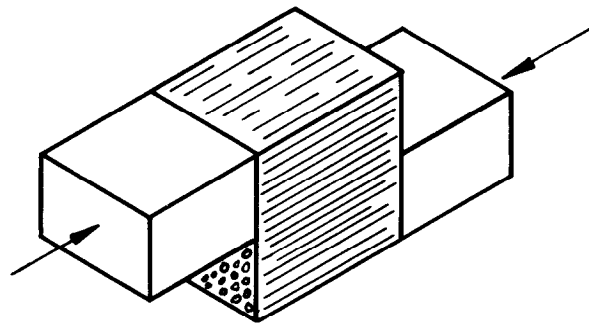
c   Punch
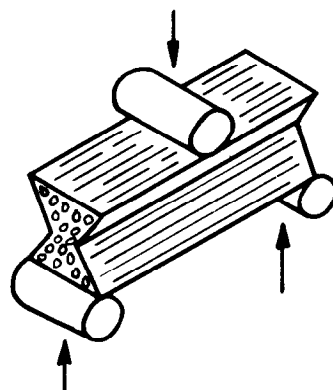
d   I beam
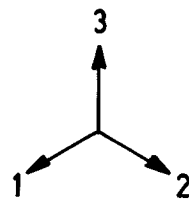
Fig 6a-d   Shear   tests   for   thick   beams
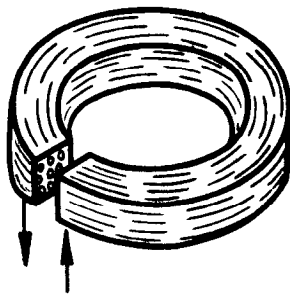
a   Split ring

b   Thin-walled tube

Fibre axes

Honeycomb

c   ± 45 sandwich

Fibre axes
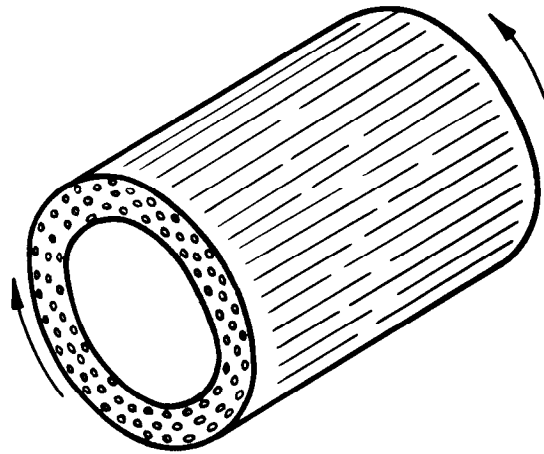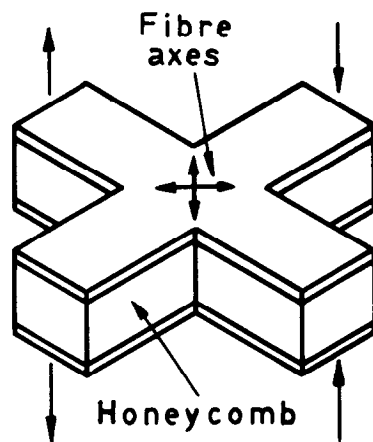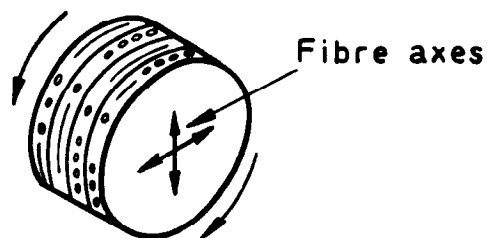
d   0+90 disc

Fig. 7a-d   Other shear tests
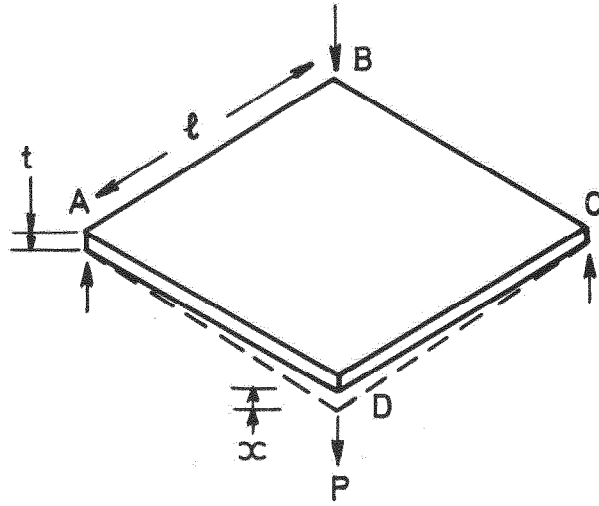
Fig.8   Plate twist test
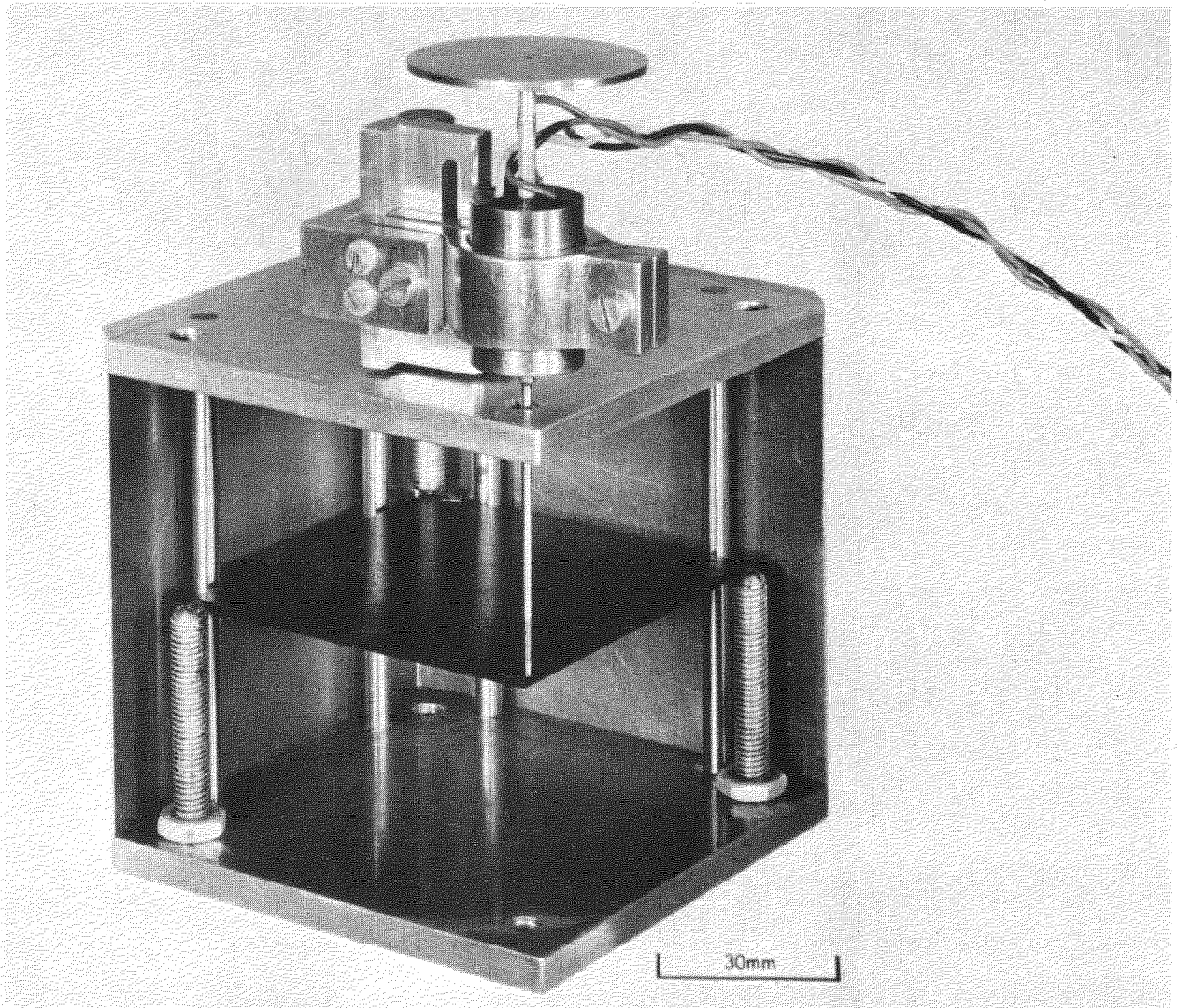
Fig.9   Plate twist – experimental rig
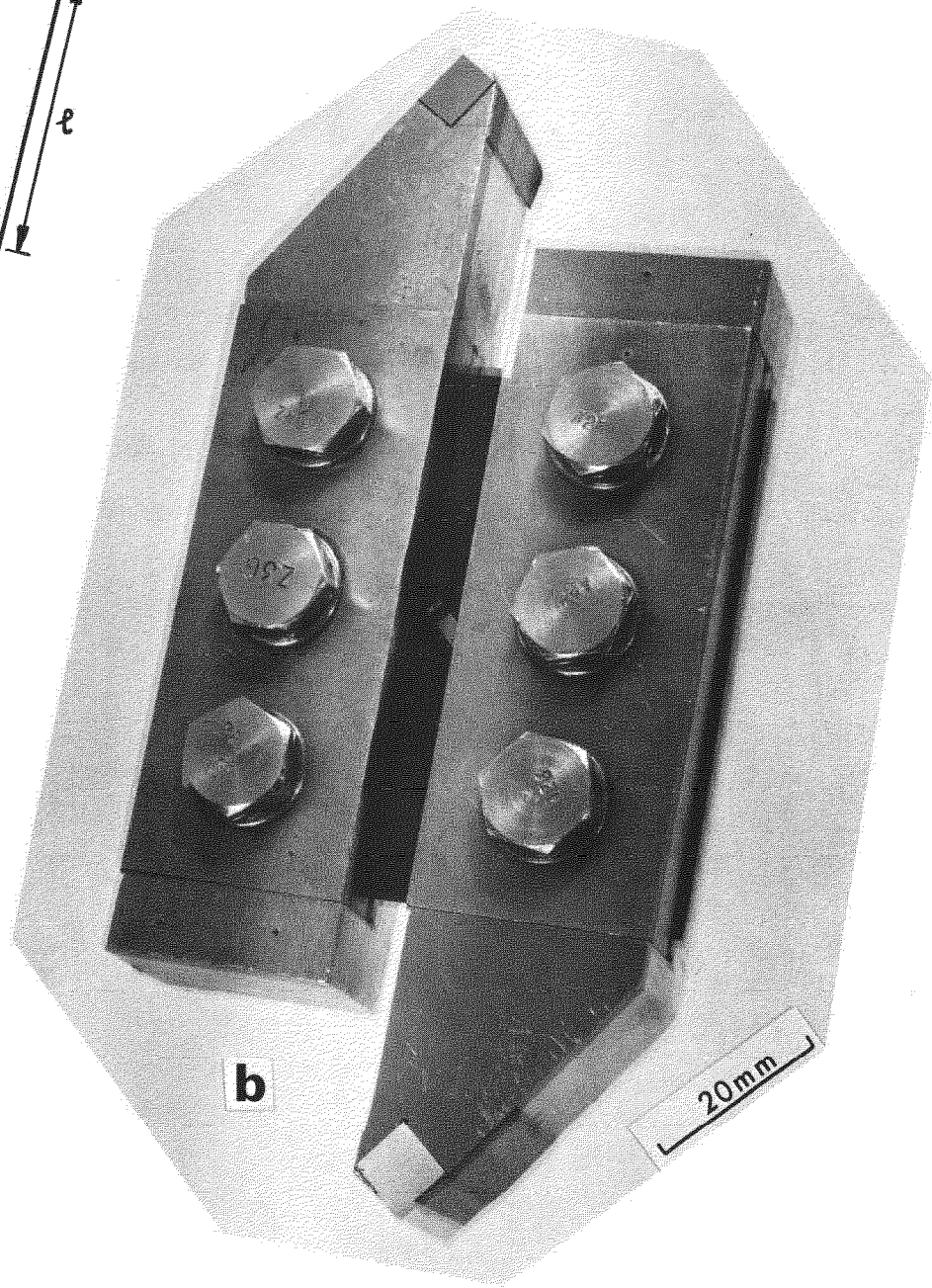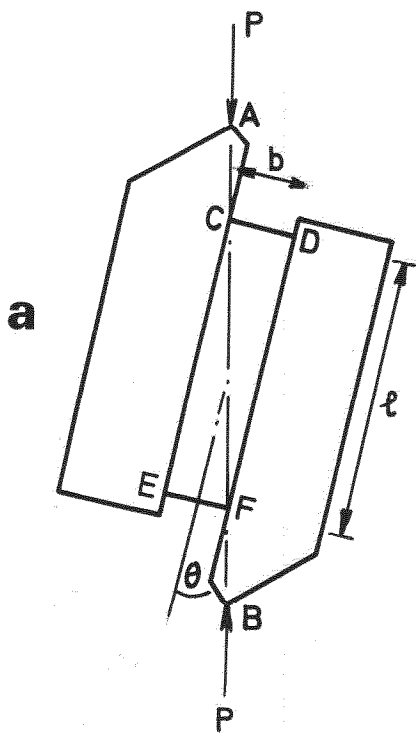
Fig.10   Rail test arrangement

P

Roller

10mm CFRP
cube

Alloy
side
plates

Strain gauges

P/₂   P/₂
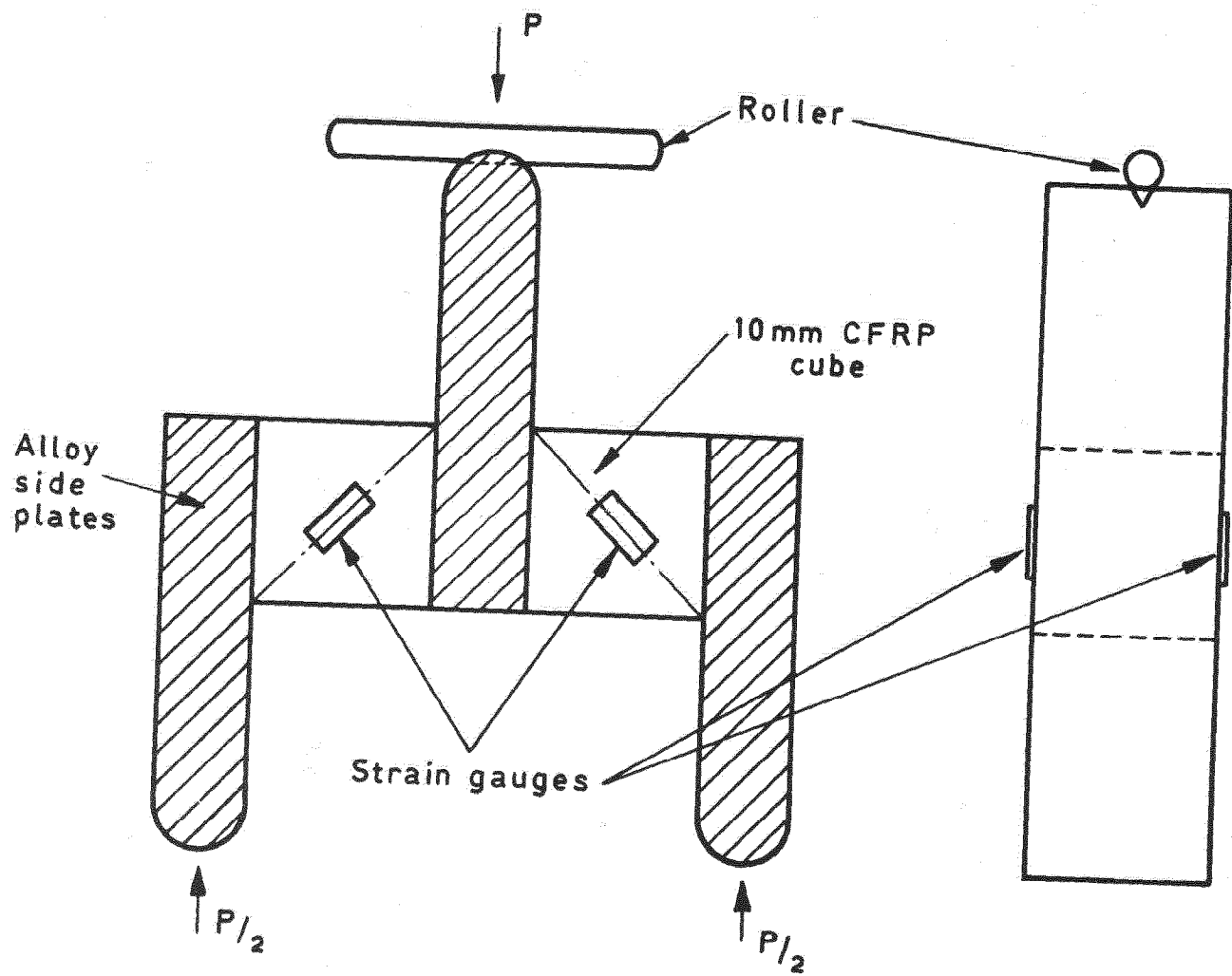
Fig.11   Modified rail test configuration
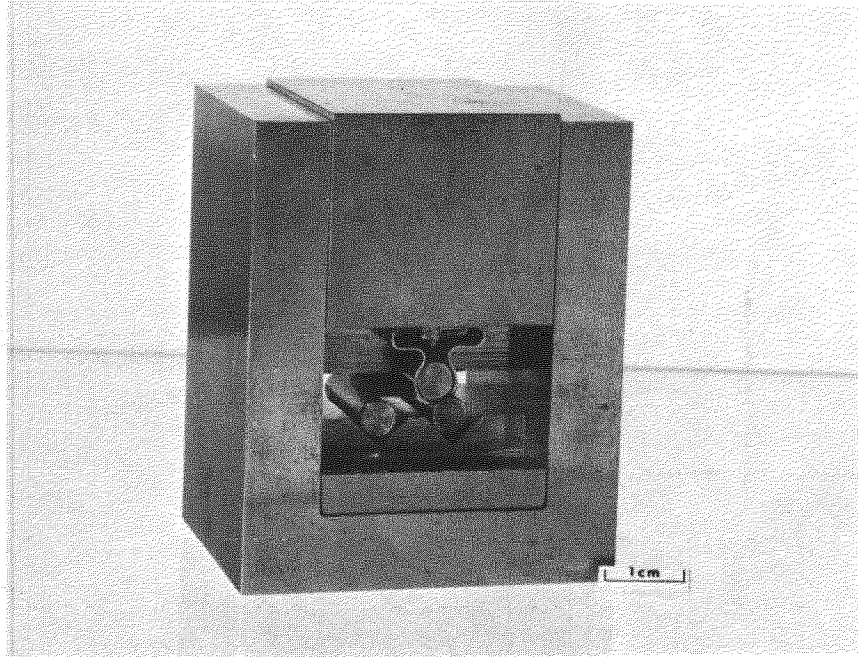
Dimensions
in mm

Fig.12   Short beam specimen

Cast epoxy

Aluminium end plate

Strain gauge

75

50

2
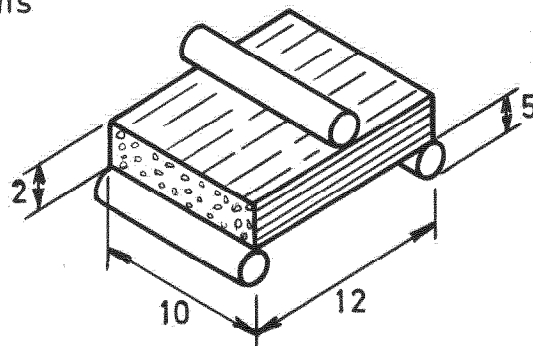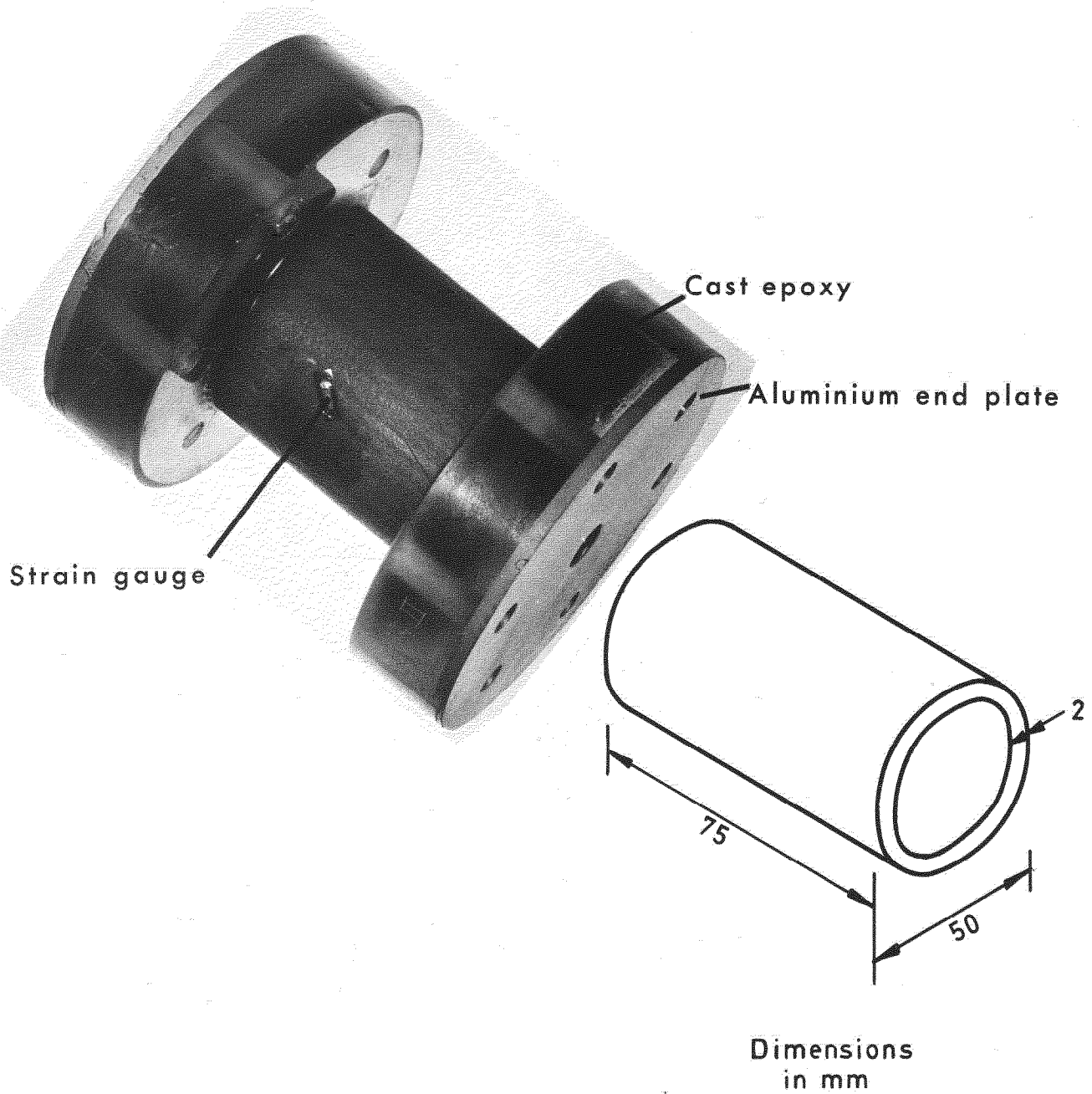
Dimensions
in mm

Fig.13   Thin-walled tube
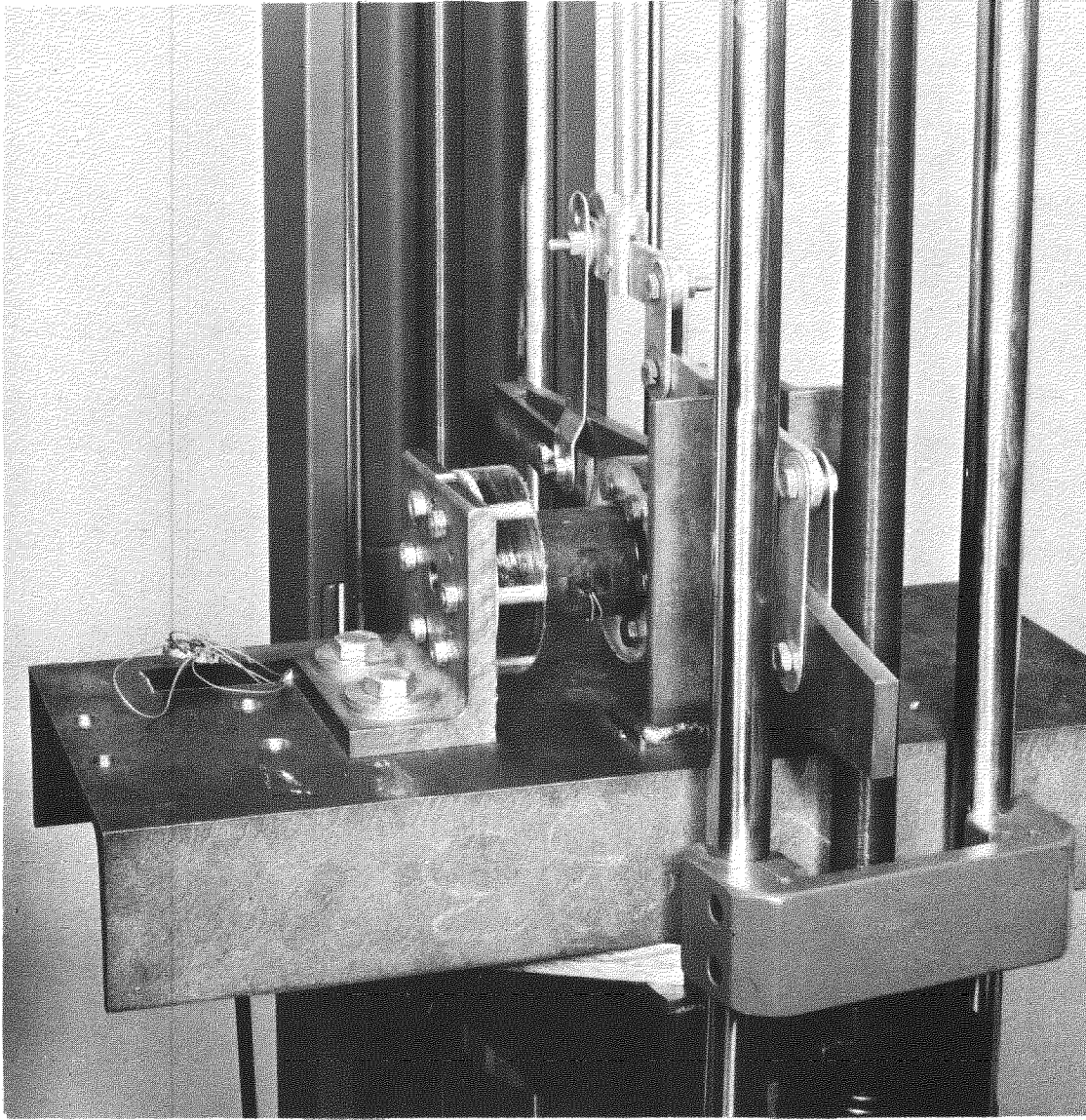
Fig.14a   Detail of tube test rig
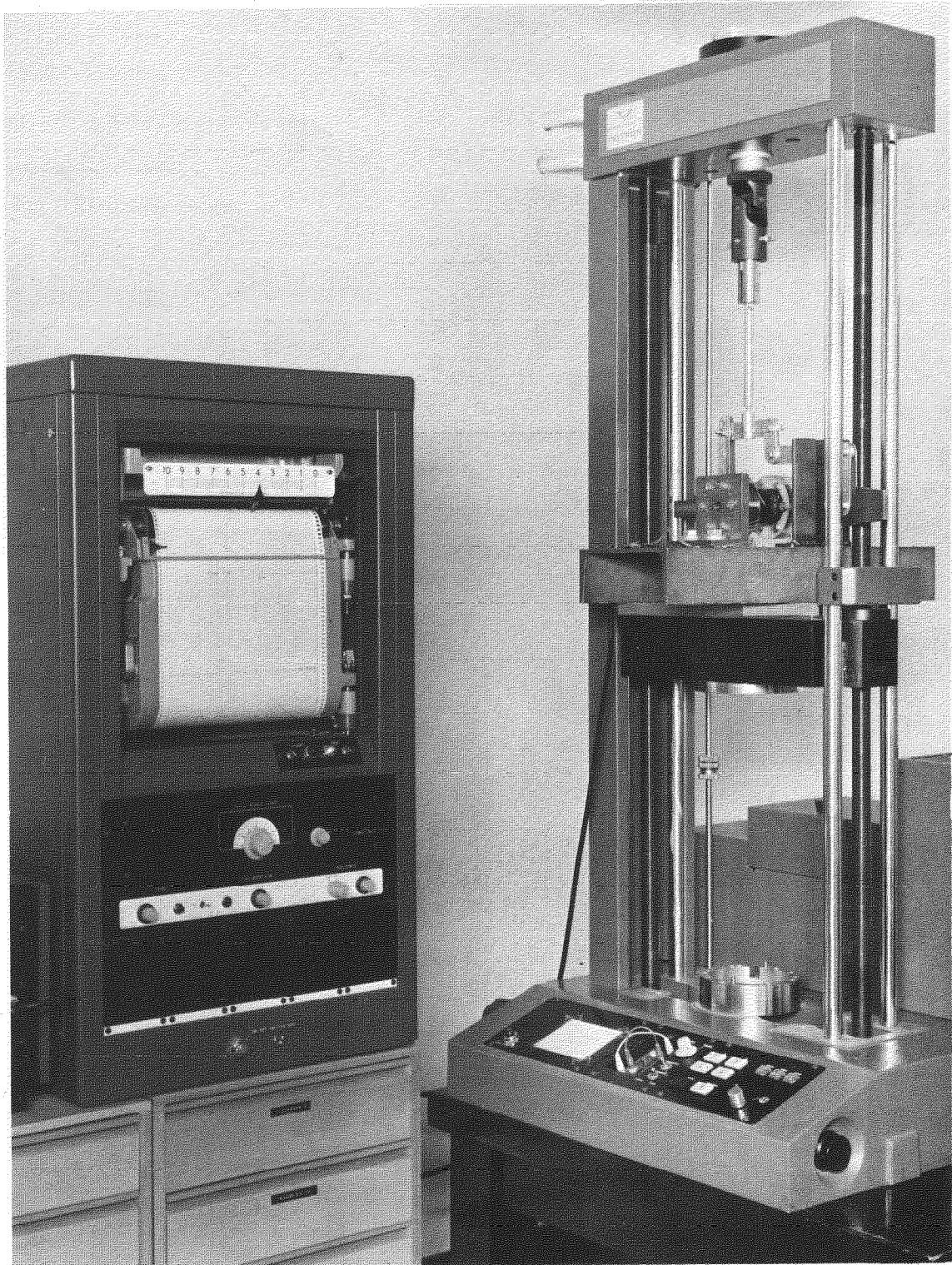
Fig.14b   General view of tube rig and servo chart drive

12·5

22·5

16

7

22·5

12·5
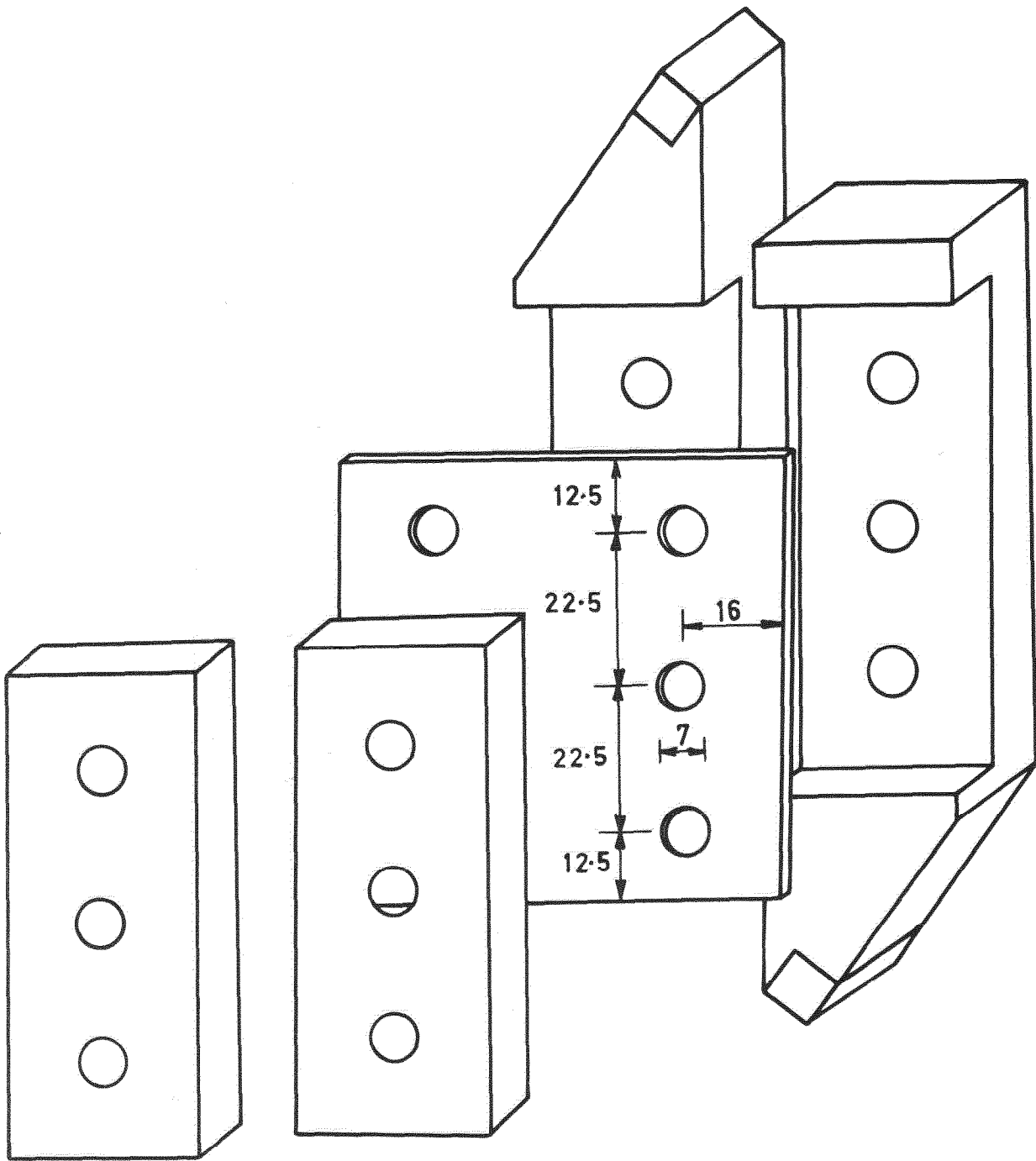
Dimensions in mm

Fig.15   Rail specimen and attachments

Fig.16   Tube moulding rig

Metal tube

Release paper

Carbon fibre pre-preg

Rubber tube

Expanding metal segments

Drain holes
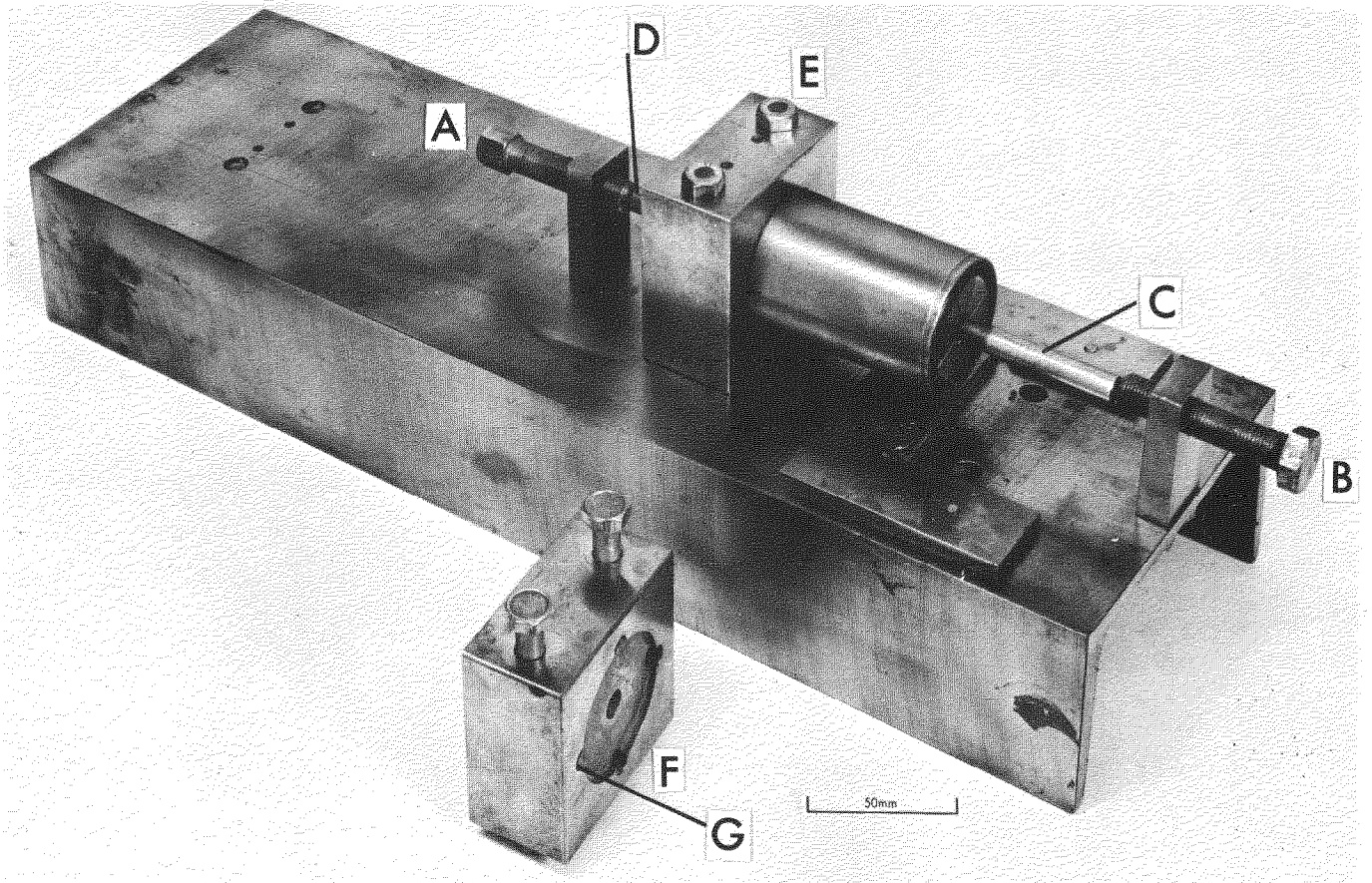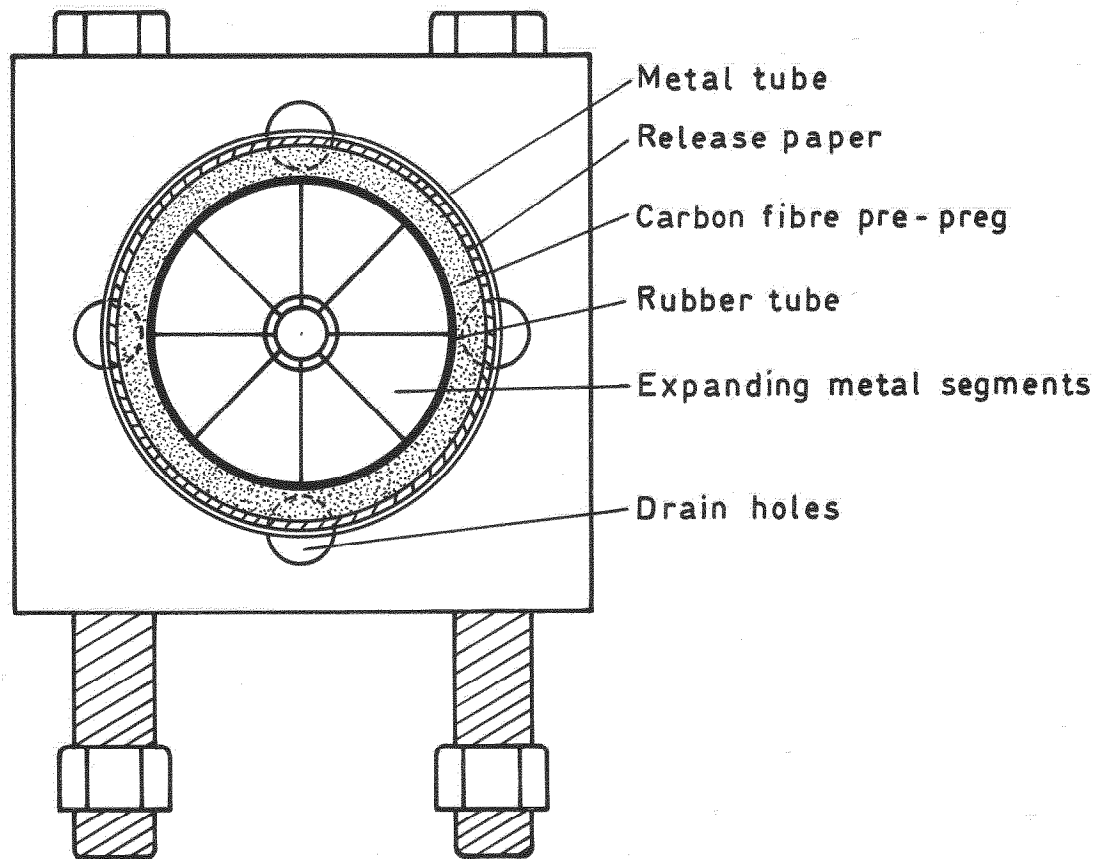
Fig.17   Tube moulding rig section
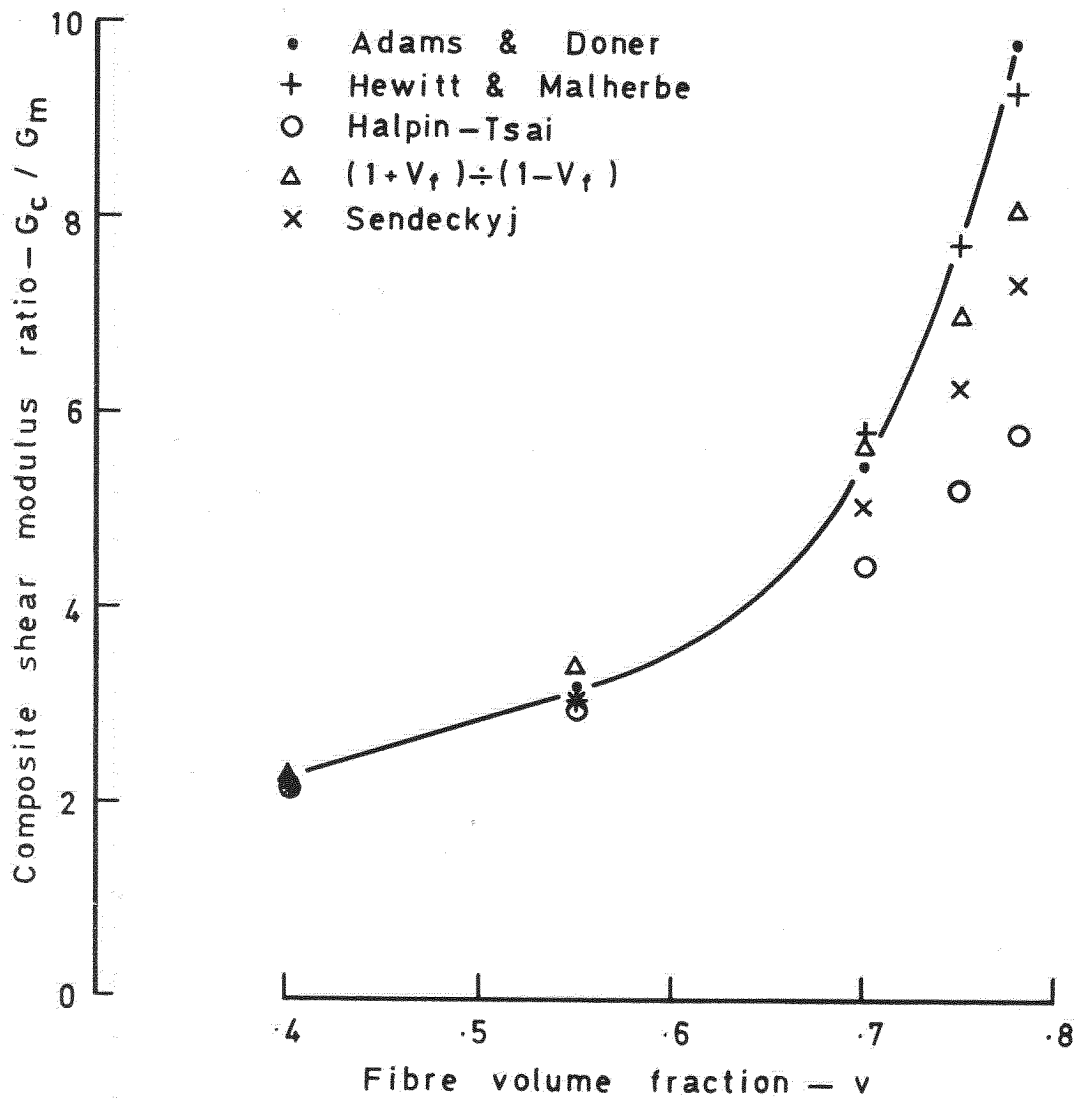
Fig.18   Predicted variation of composite shear modulus with fibre volume fraction
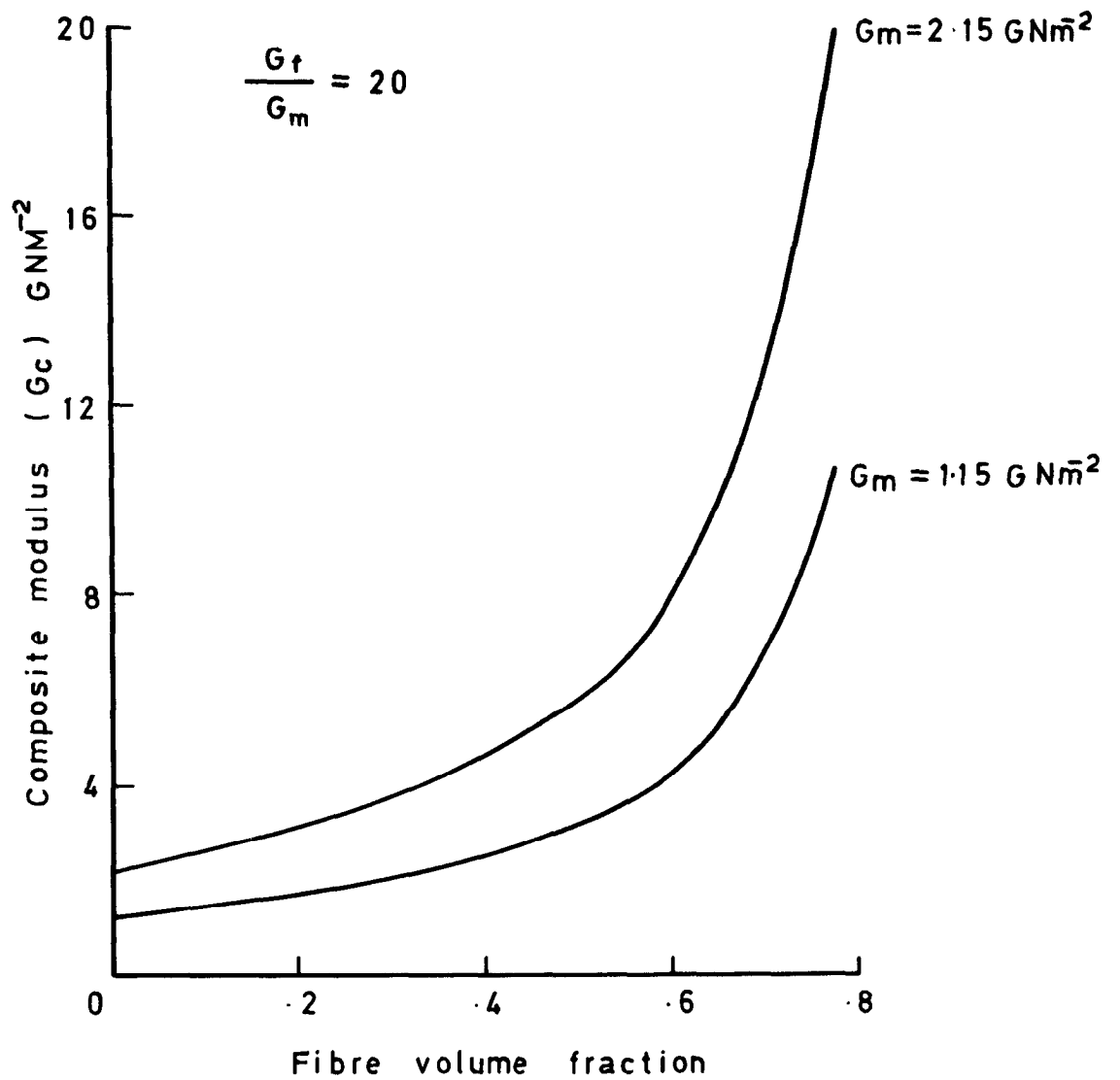
Fig.19   Predicted shear moduli for typical
resin matrices (Ref. 63)
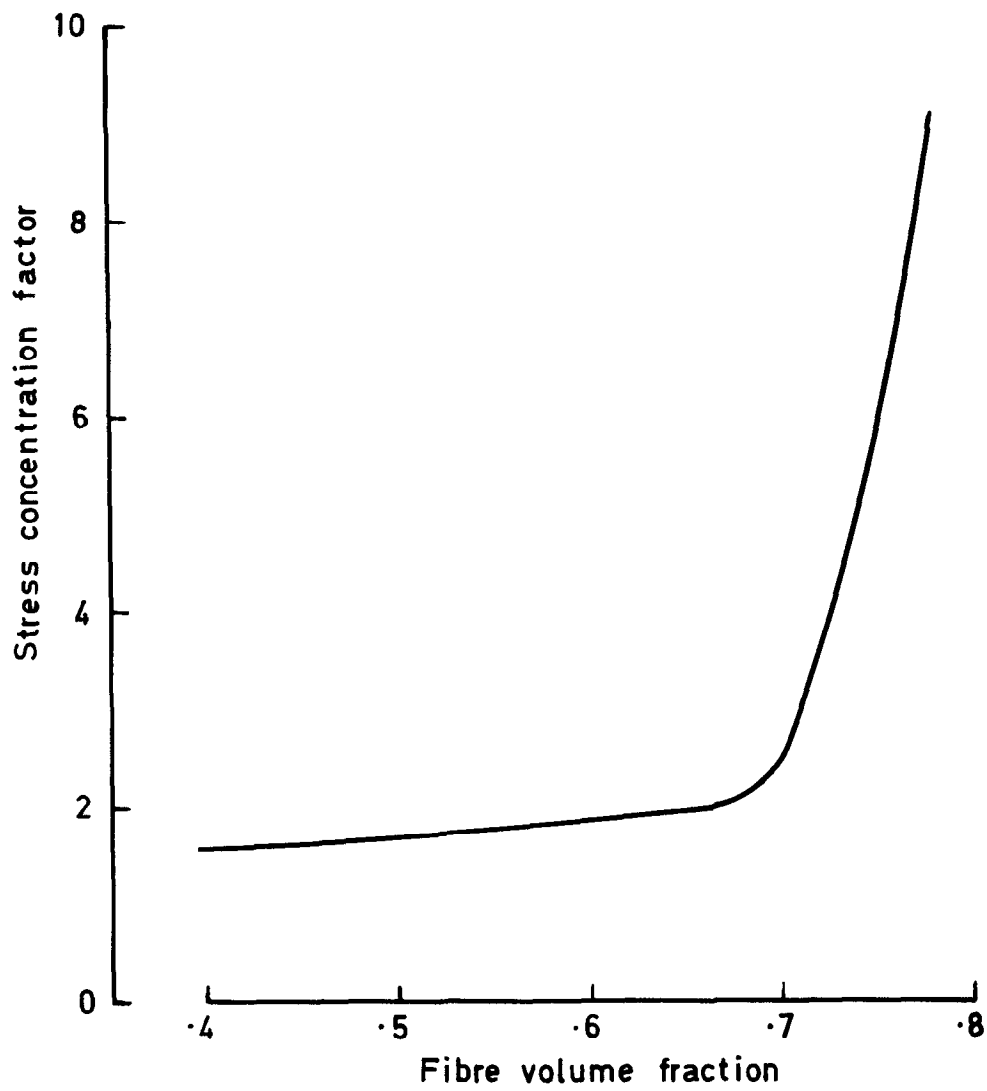
Fig.20   Stress concentration factor (Ref. 59)
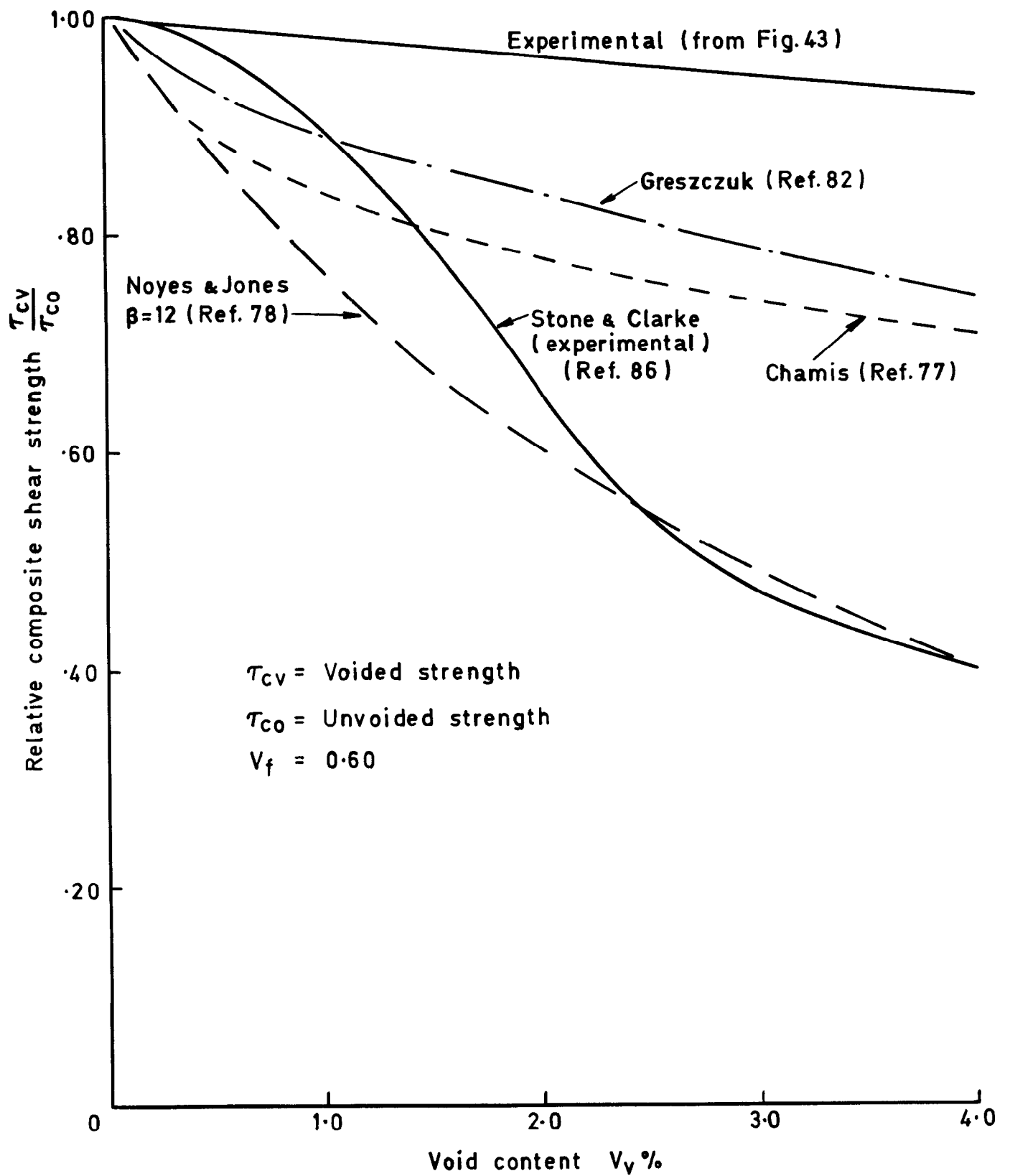
Fig.21 Variation of shear strength with void content

Fig. 22   Shear   modulus – Plate   Twist – Type I

Composite shear modulus GNm⁻² is displayed along the vertical axis with values from 0 to 9.

Legend:
■ □ Unidirectional 0° measured
● □ Unidirectional 90° measured
□ ○ Void corrected

Equation 8

Fibre volume fraction
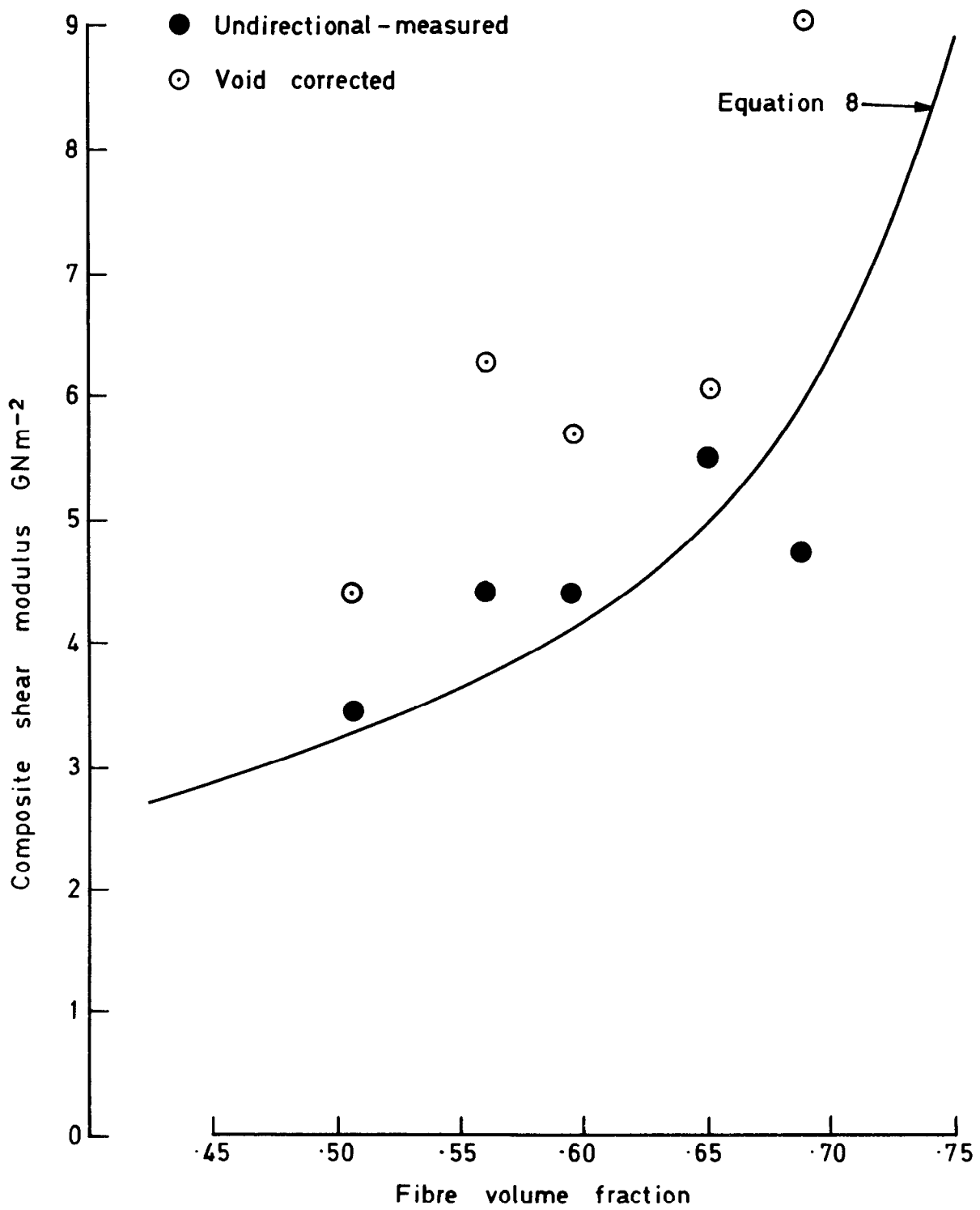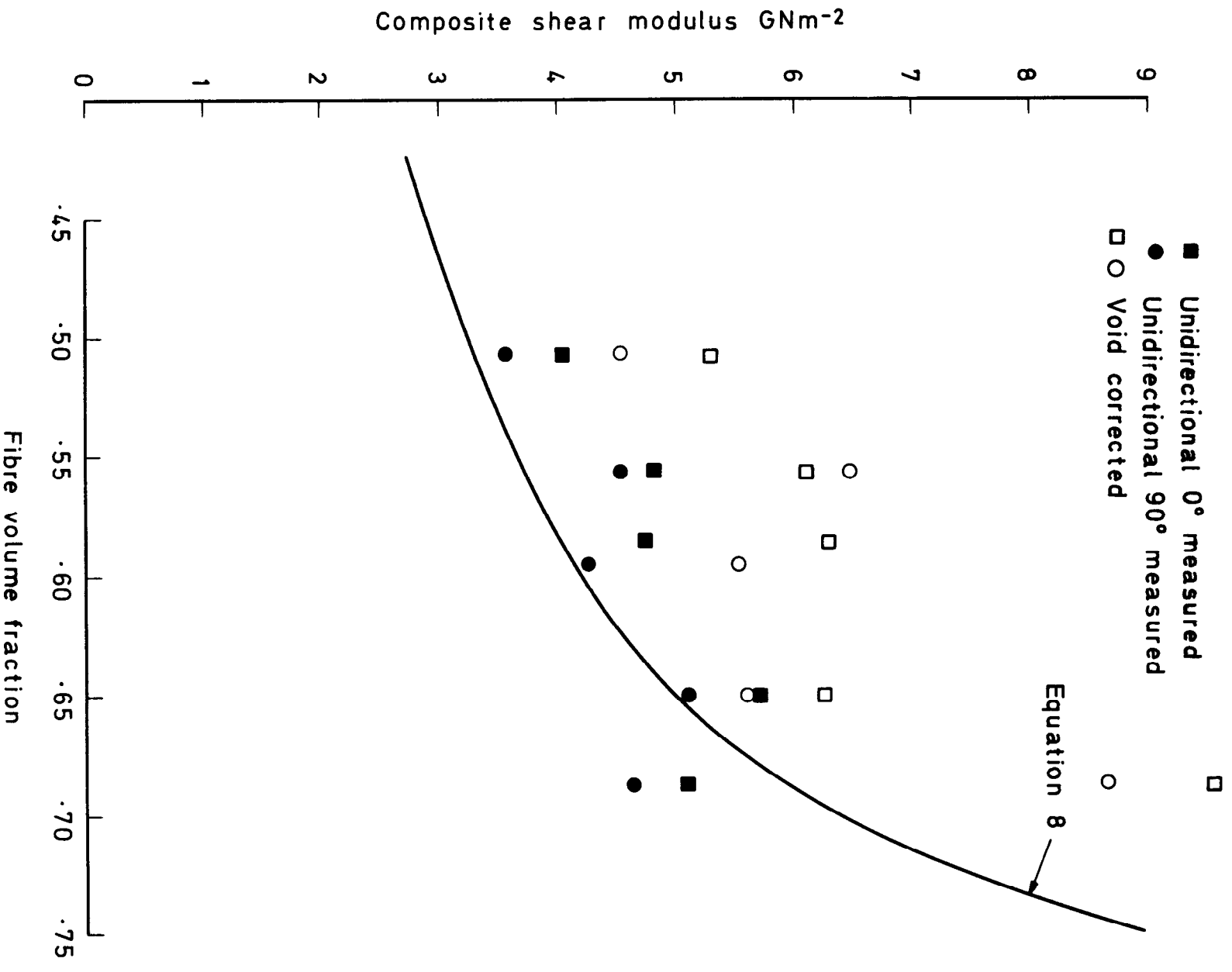
Fig. 23   Shear modulus – Rail – Type I
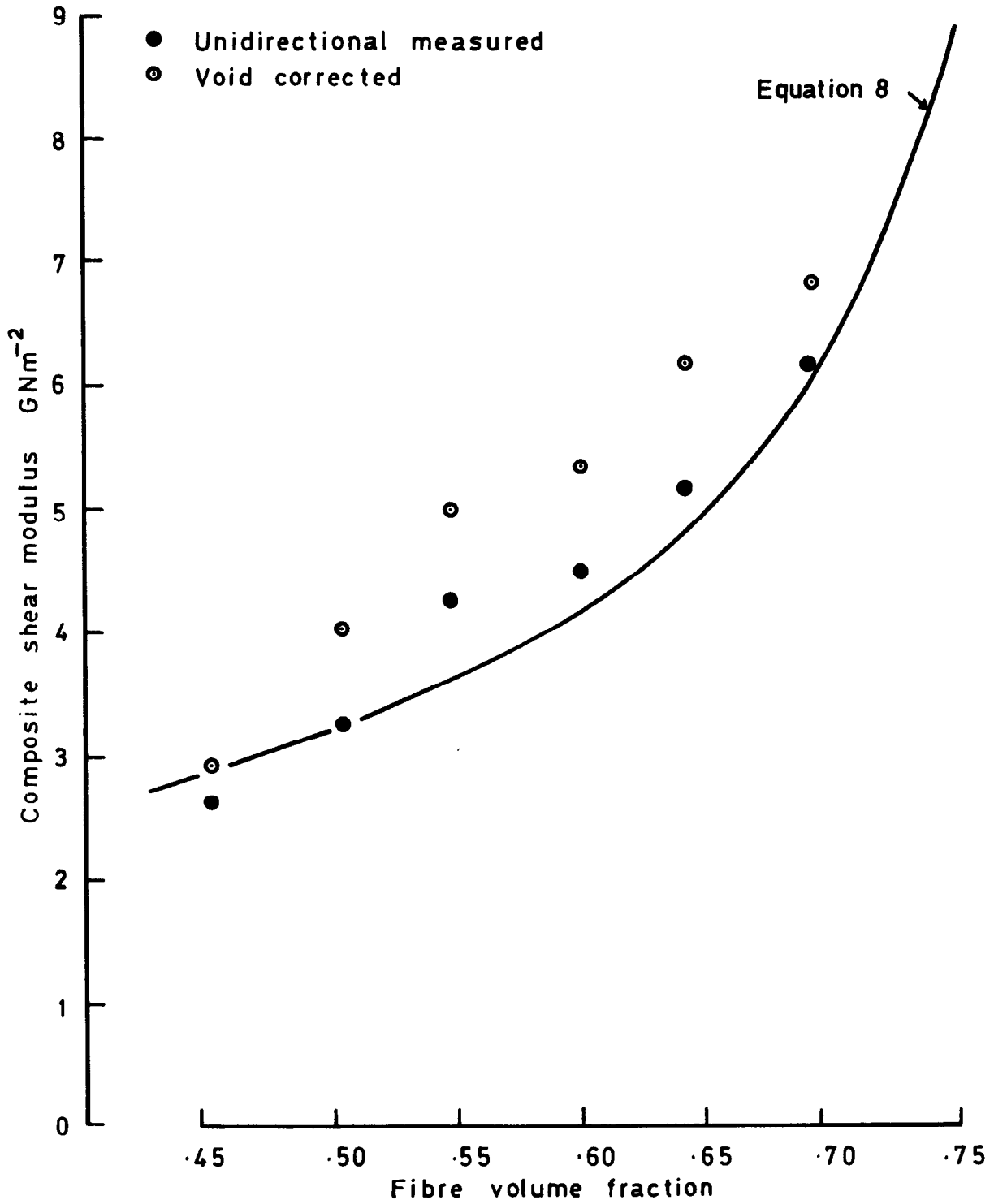
Fig.24   Shear modulus—Plate Twist—Type II
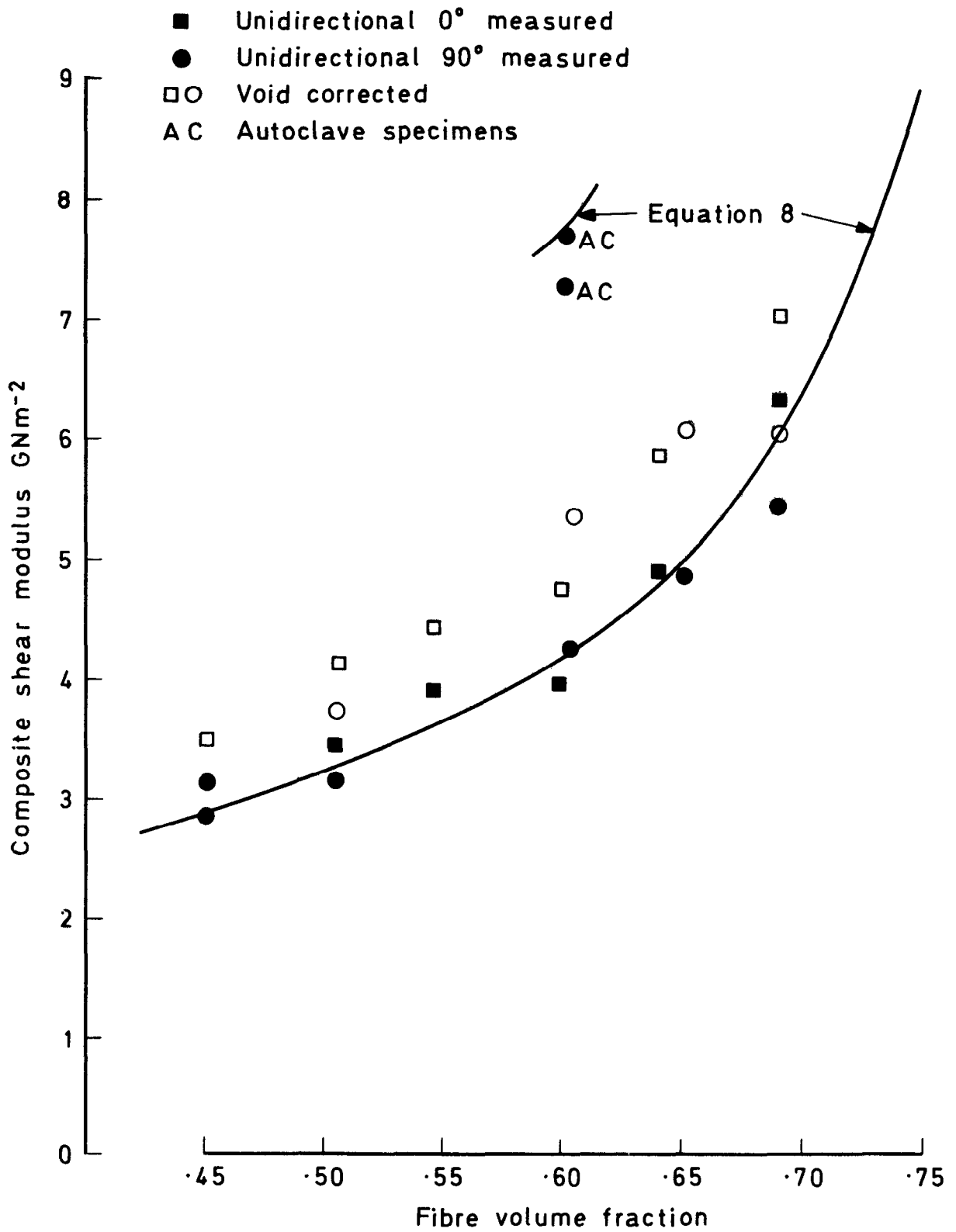
Fig. 25   Shear modulus – Rail –Type II
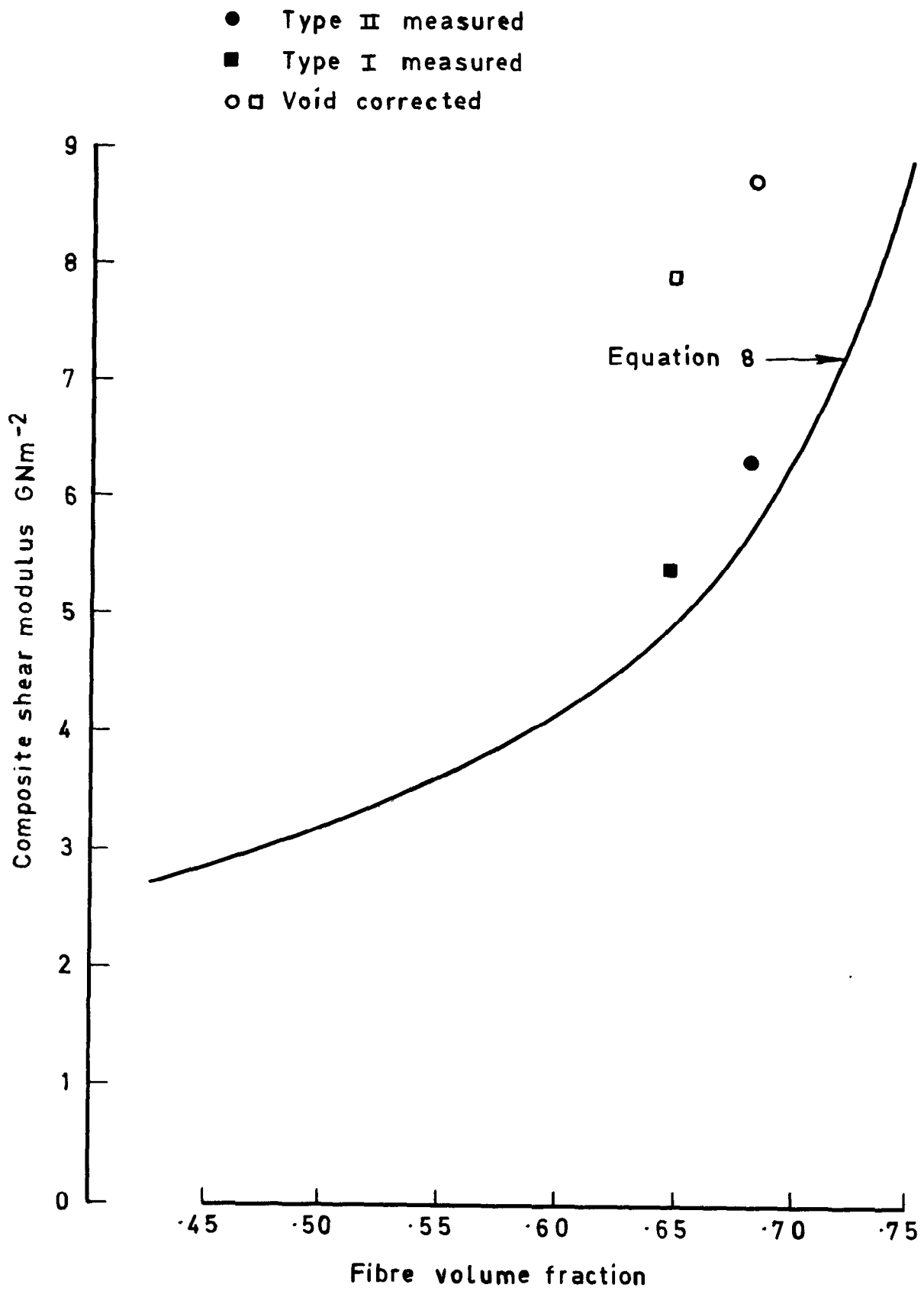
Fig. 26   Shear modulus – Tubes
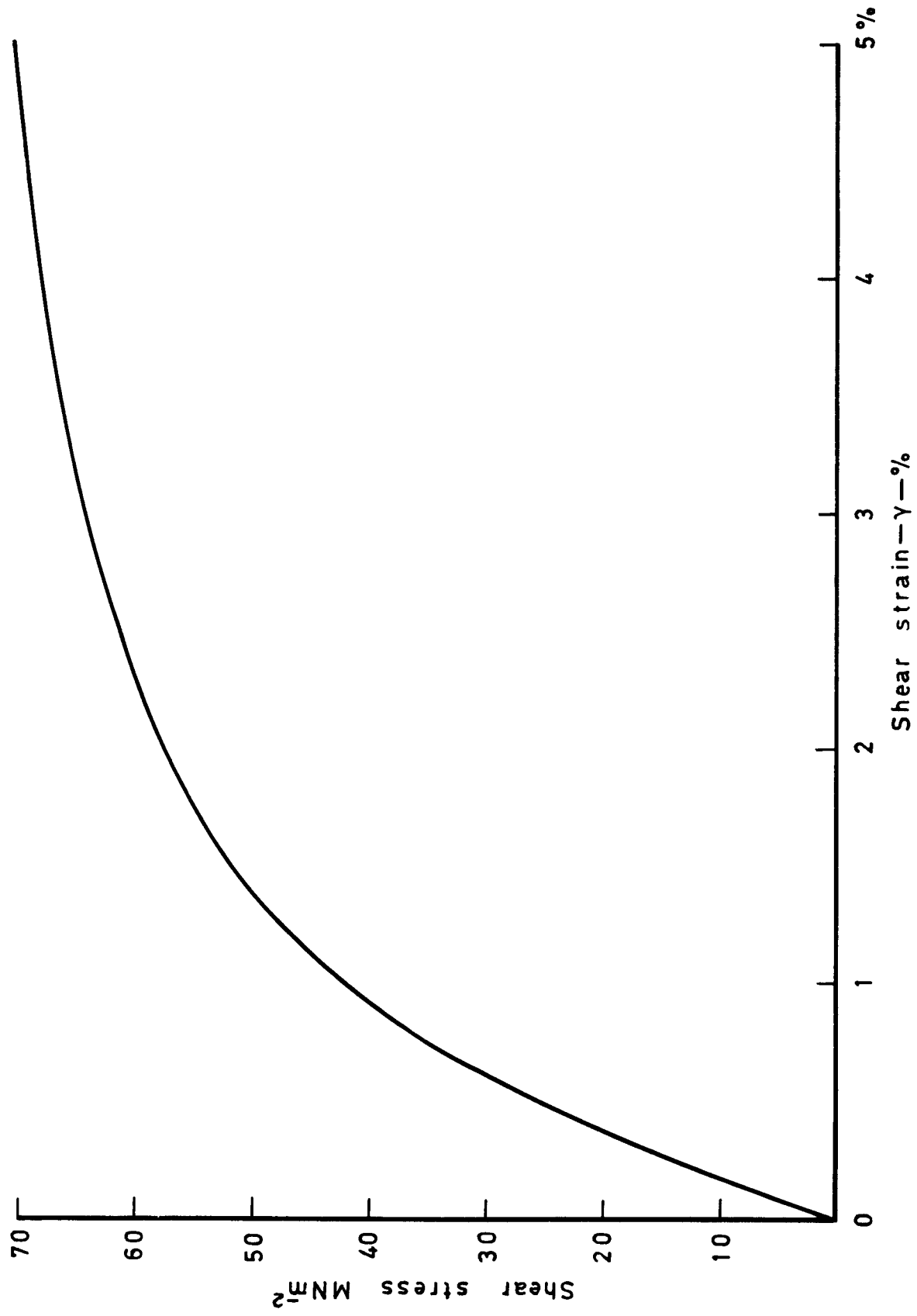
Fig. 27 Typical stress/strain curve—Rail—Type I
(of tubes, 7,8,9,10)
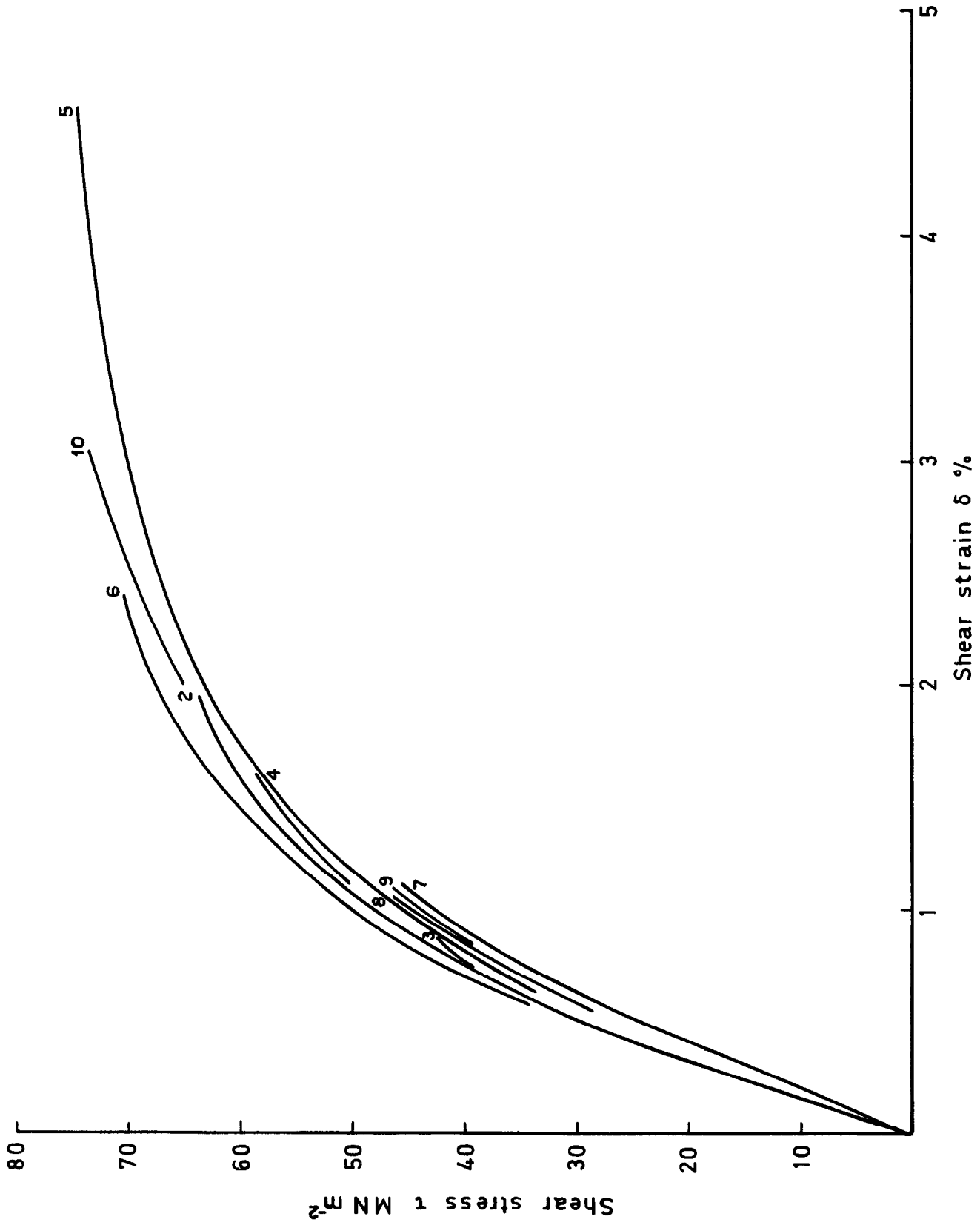
Fig.28   Stress/strain curve to failure — Tubes
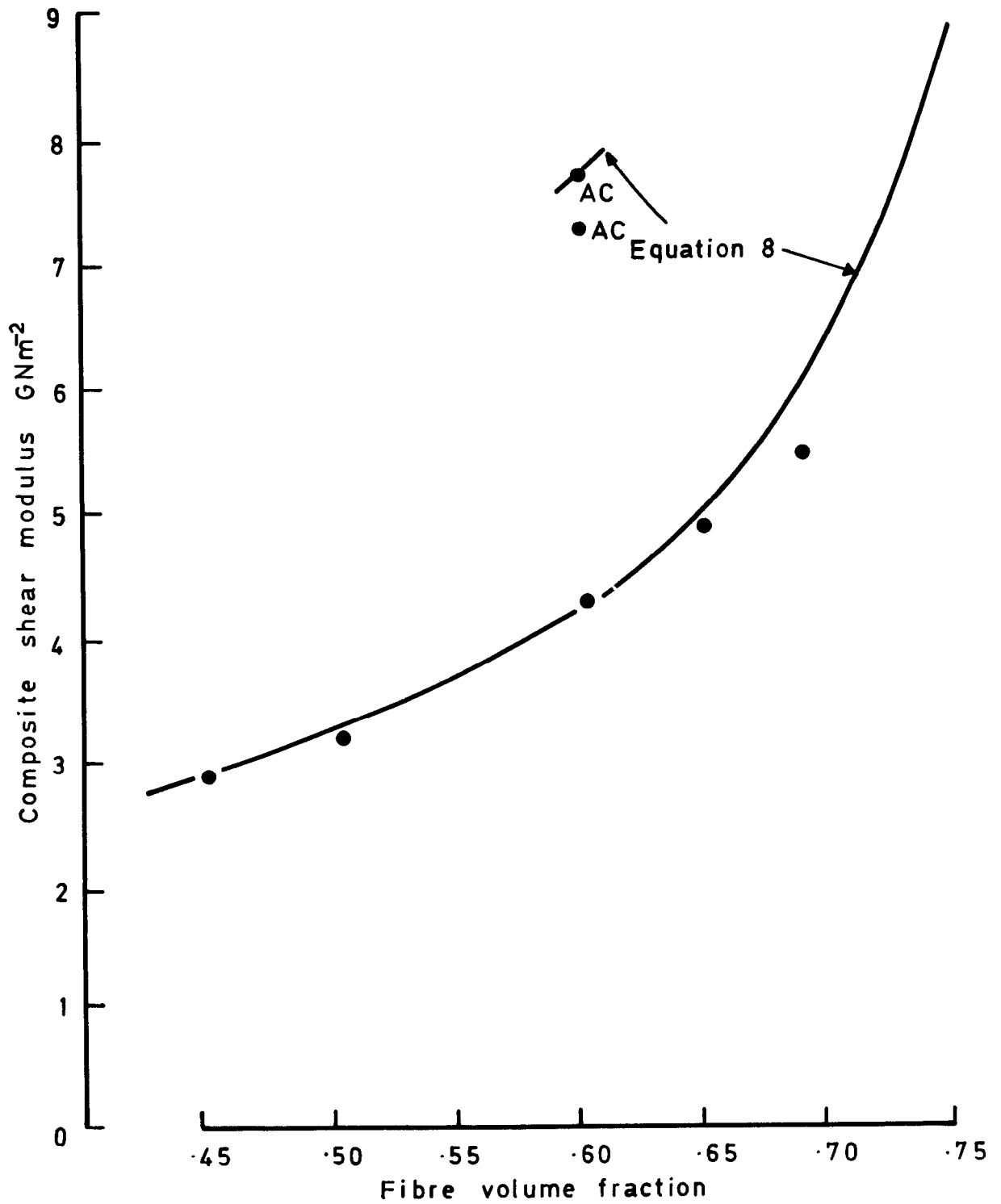
Fig.29   Shear modulus − 90° Rail   shear   Type Ⅱ &   Theory
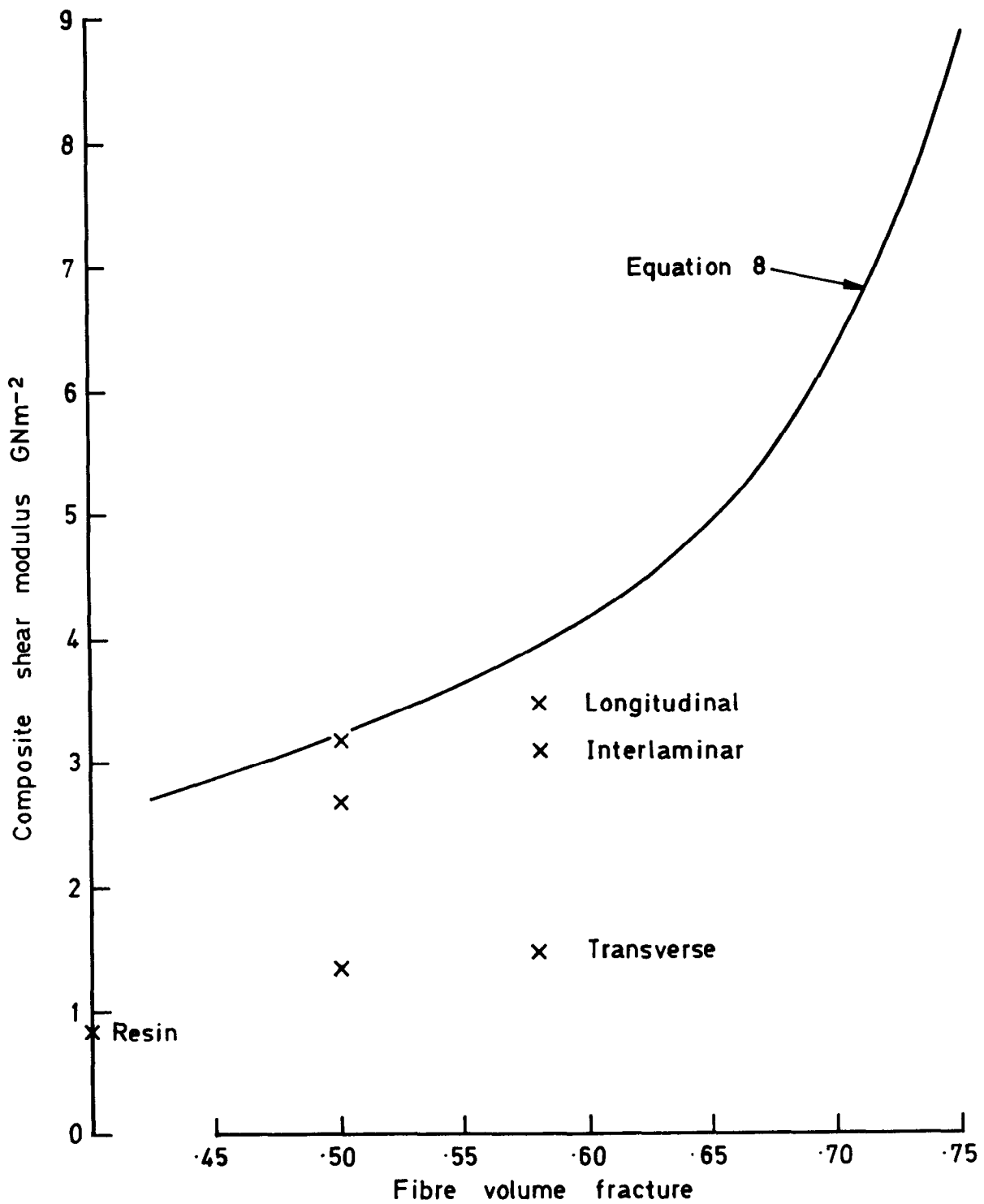
Fig. 30   Shear moduli in the three principal planes
(for   AC   type I fibre composite)
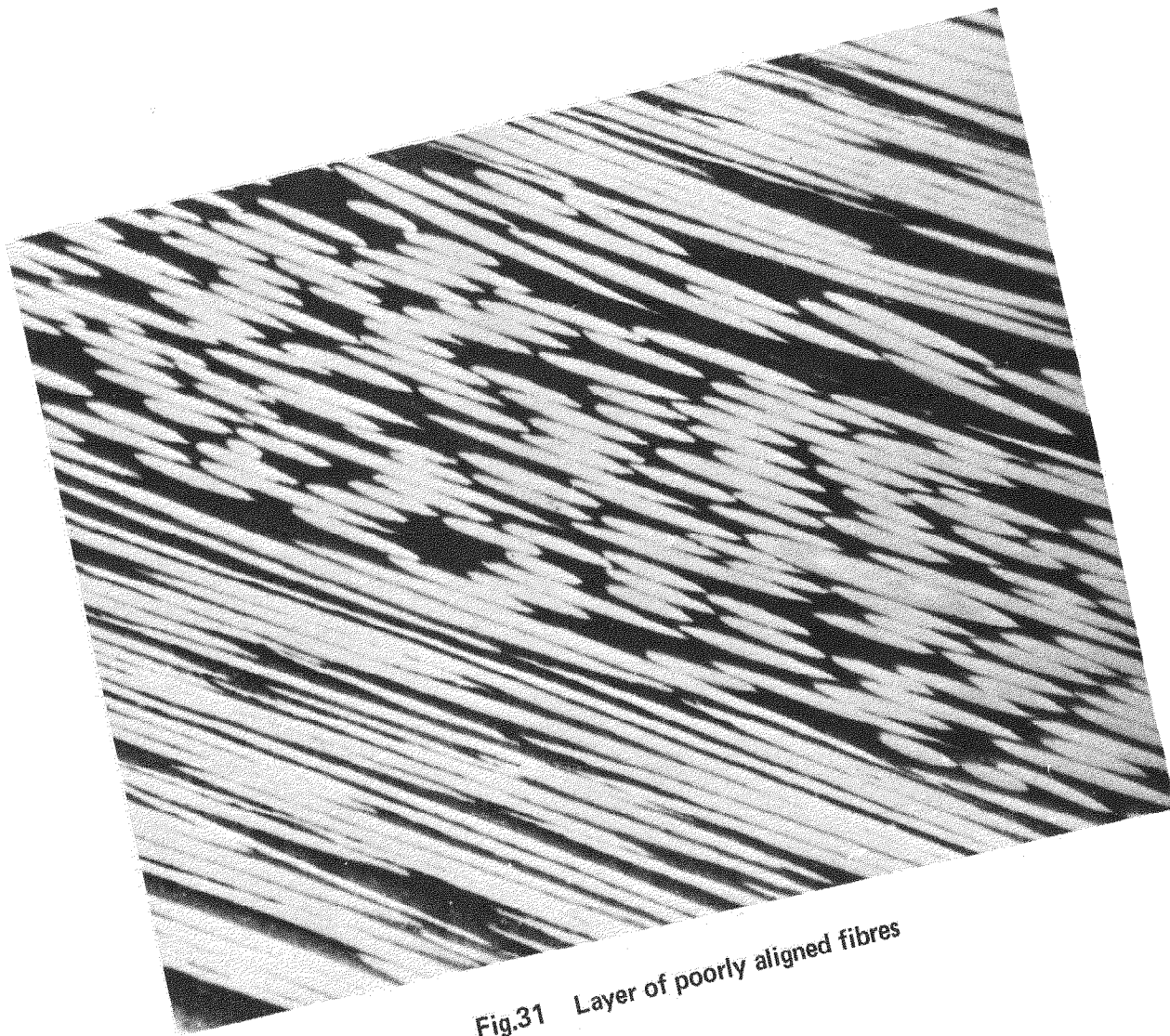
Fig.31   Layer of poorly aligned fibres
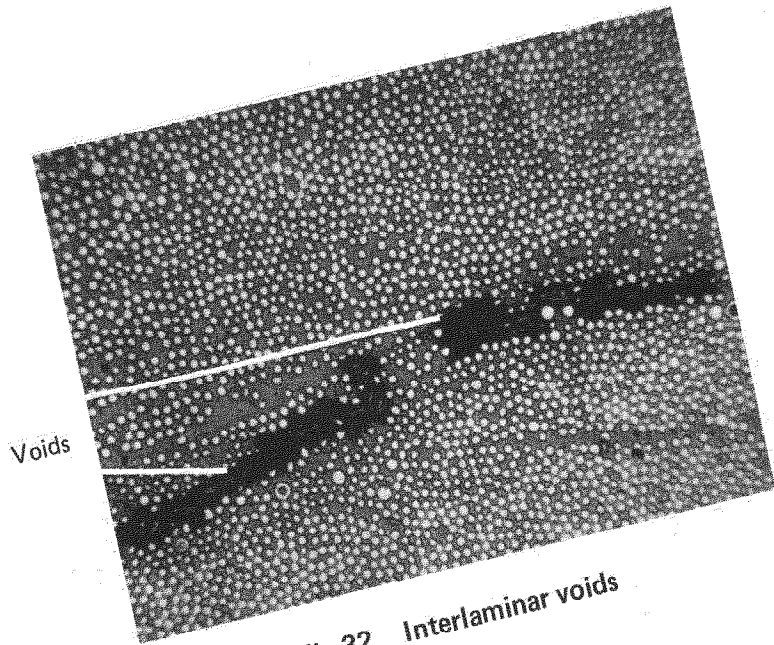
Voids

Fig.32   Interlaminar voids

For this laminate measured strength was found
to be almost independent of void content
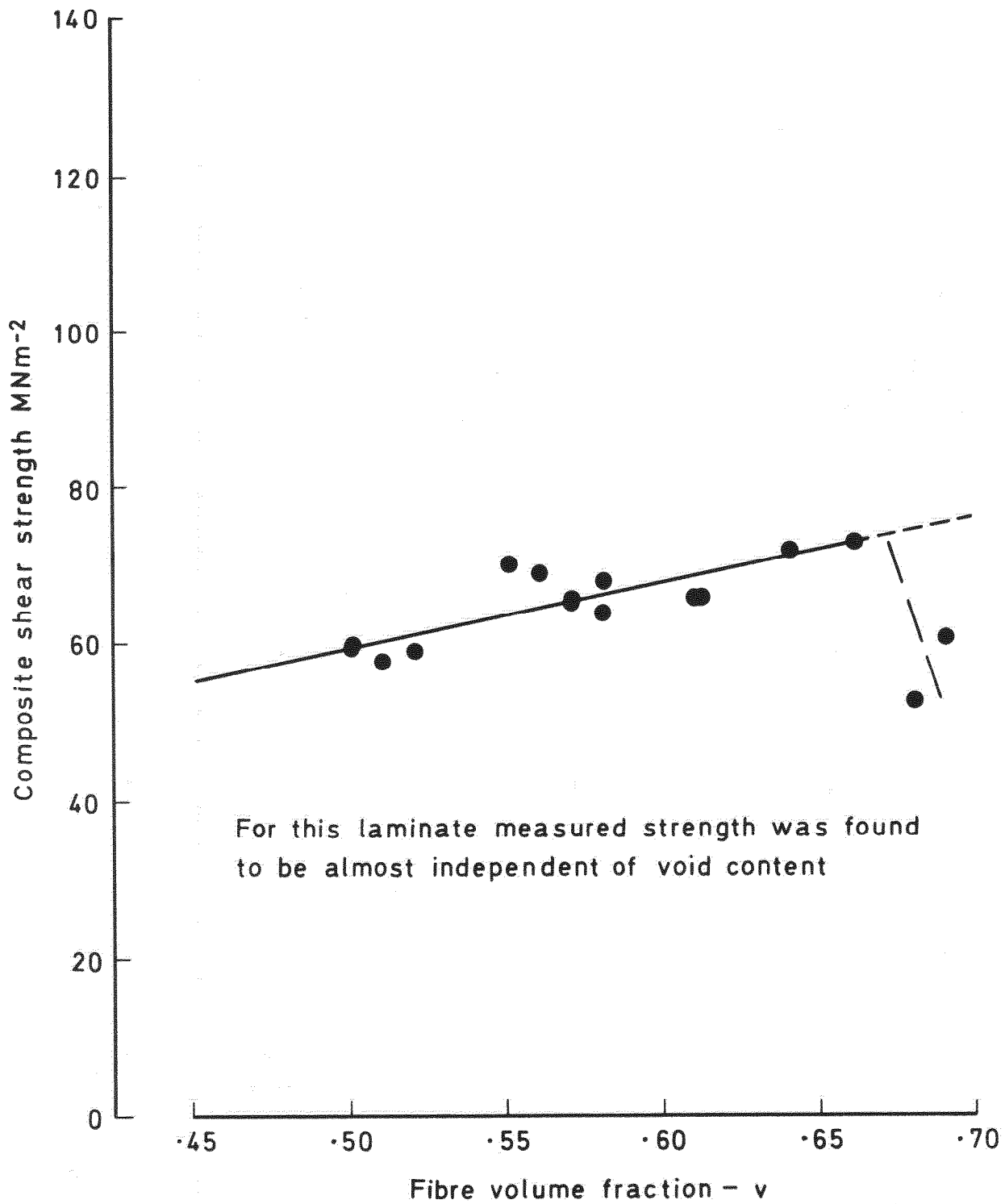
Fig. 33   Variation of shear strength with fibre content.
Rail – Type I
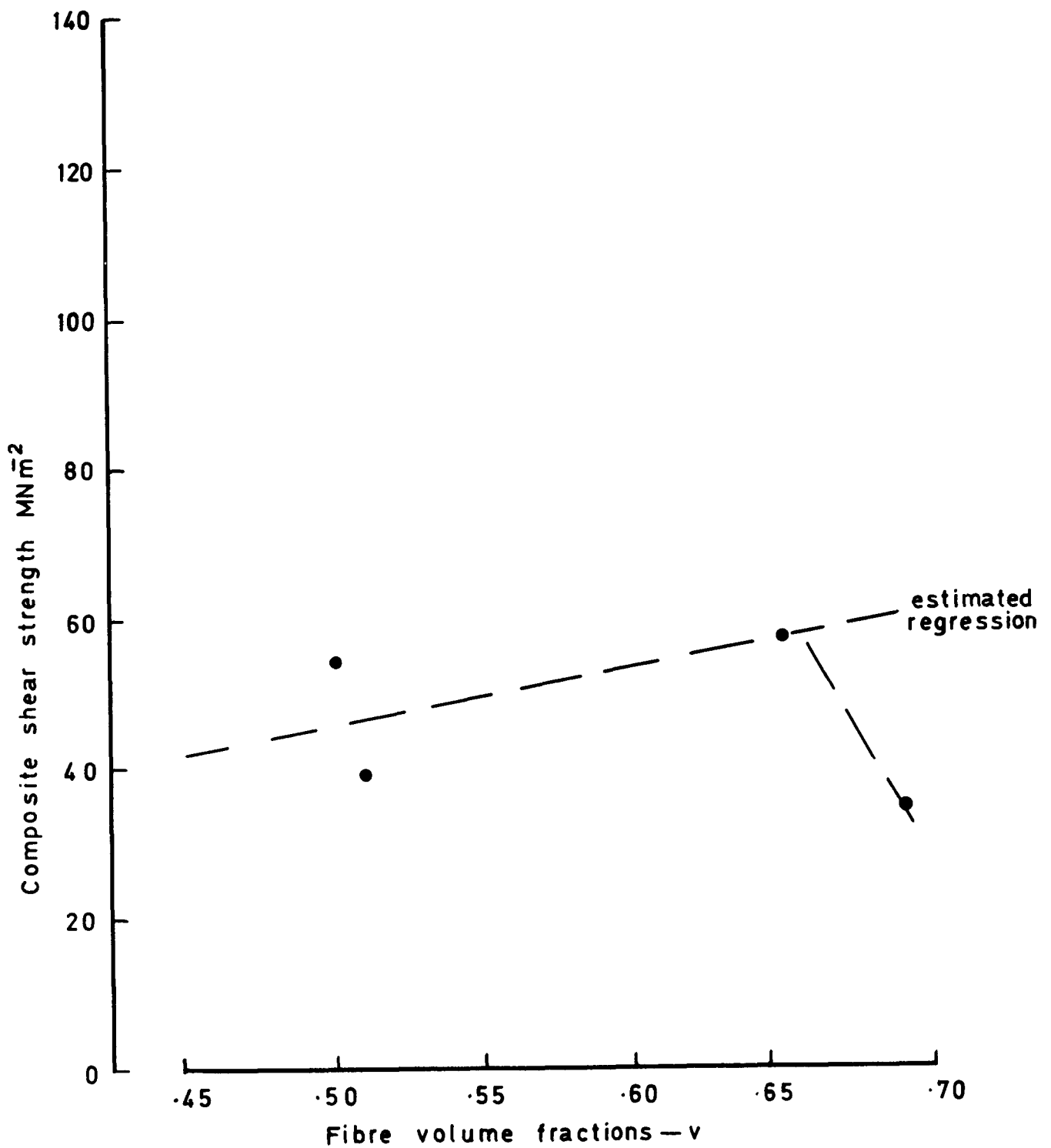
Fig. 34   Variation of shear strength with fibre content.
Short beam — Type I
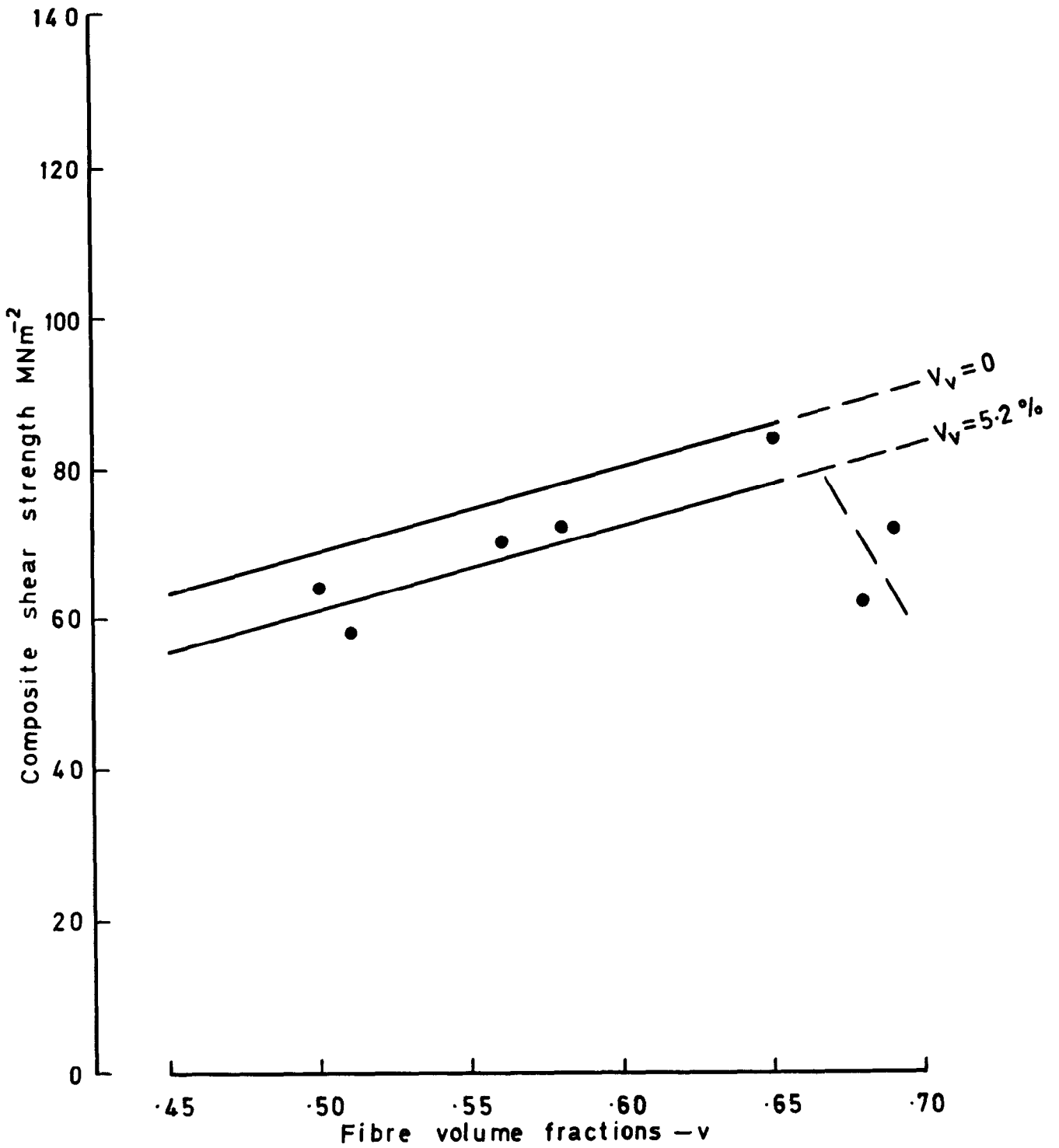
Fig. 35   Variation of shear strength with fibre content.
Transverse   compression—Type II
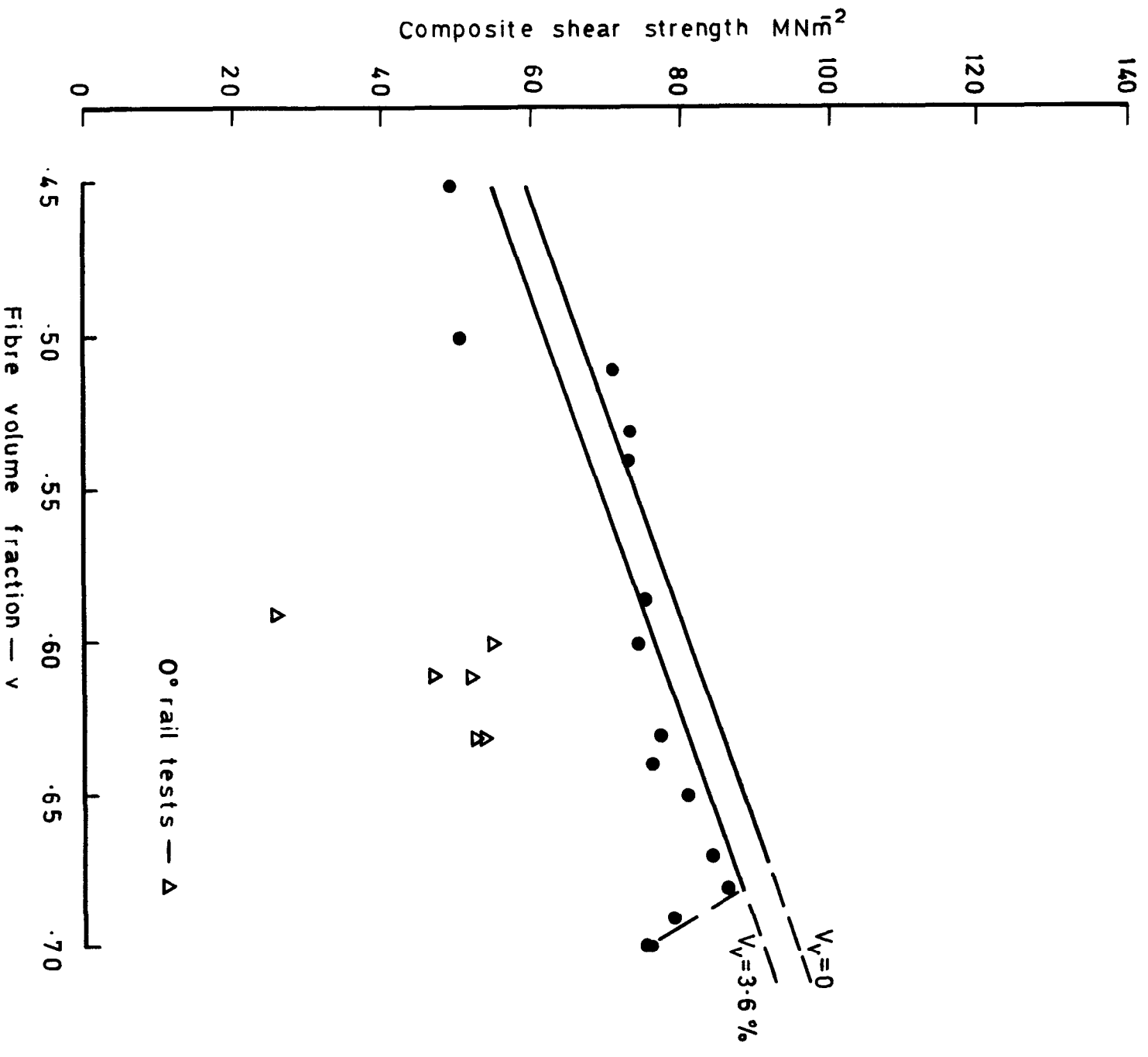
Fig.36   Variation of shear strength with fibre content.
Rail—Type Ⅱ
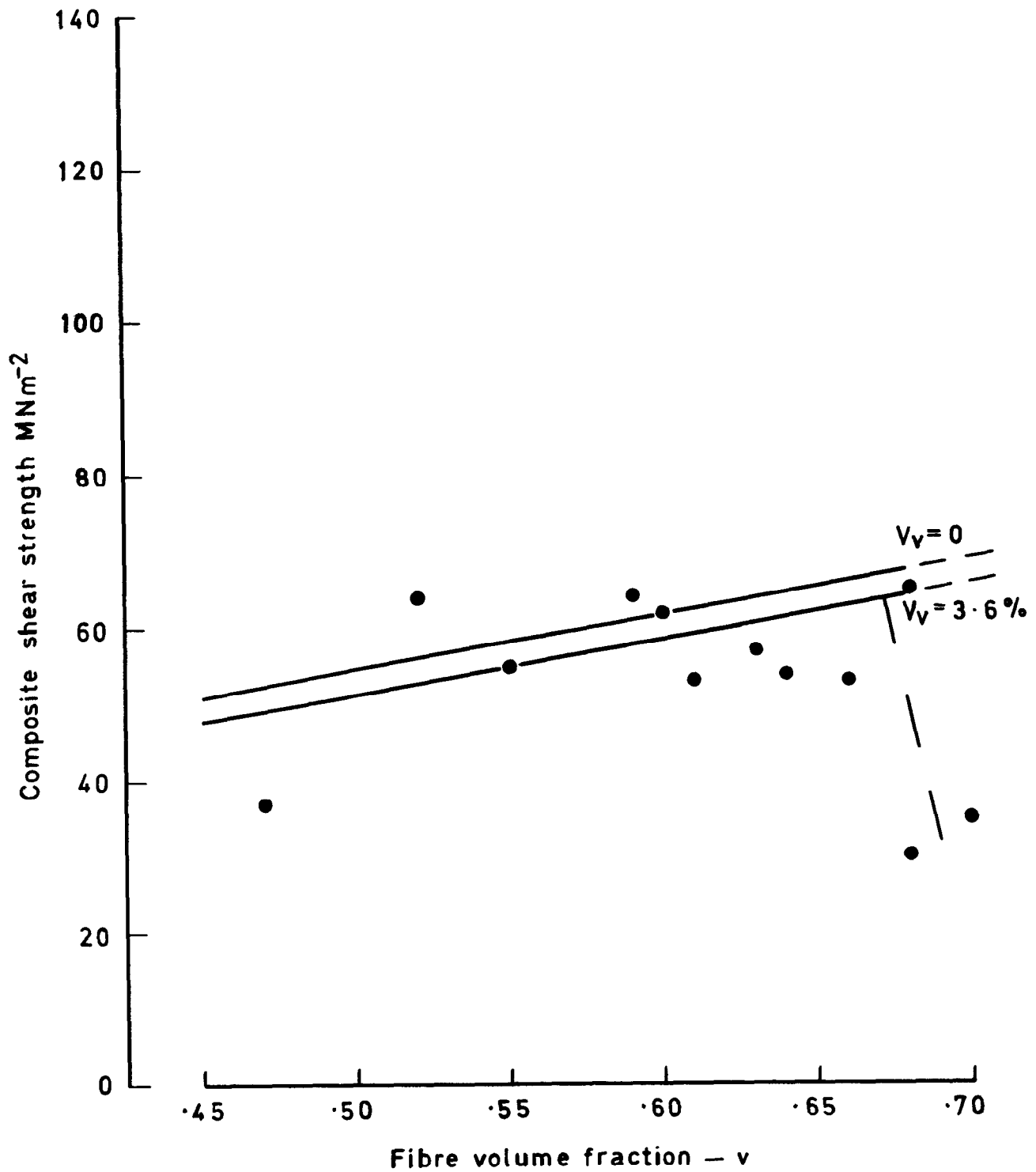
Fig. 37   Variation of shear strength with fibre content.
Short beam —Type II
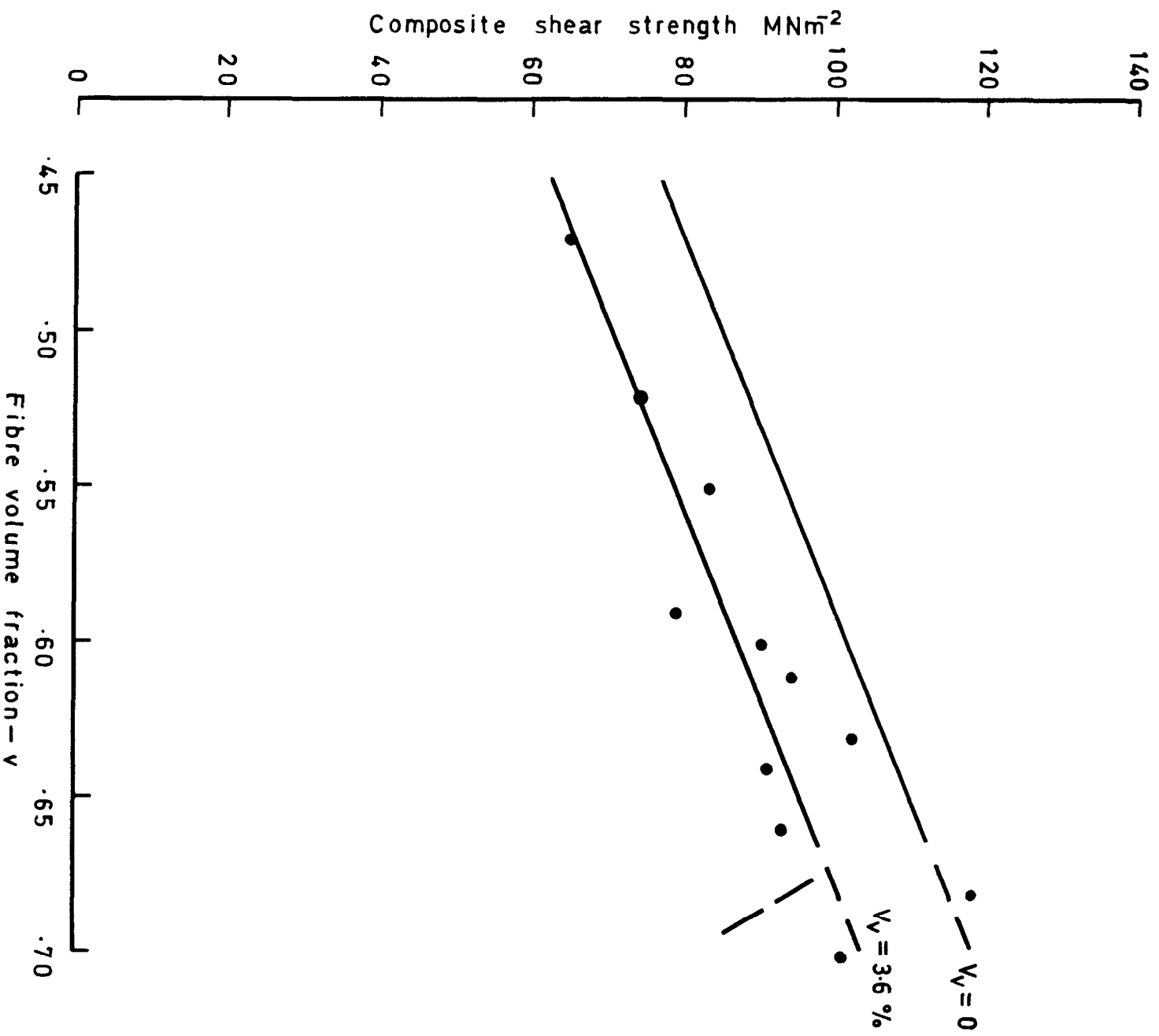
Fig. 38 Variation of shear strength with fibre content.
Transverse compression—Type II
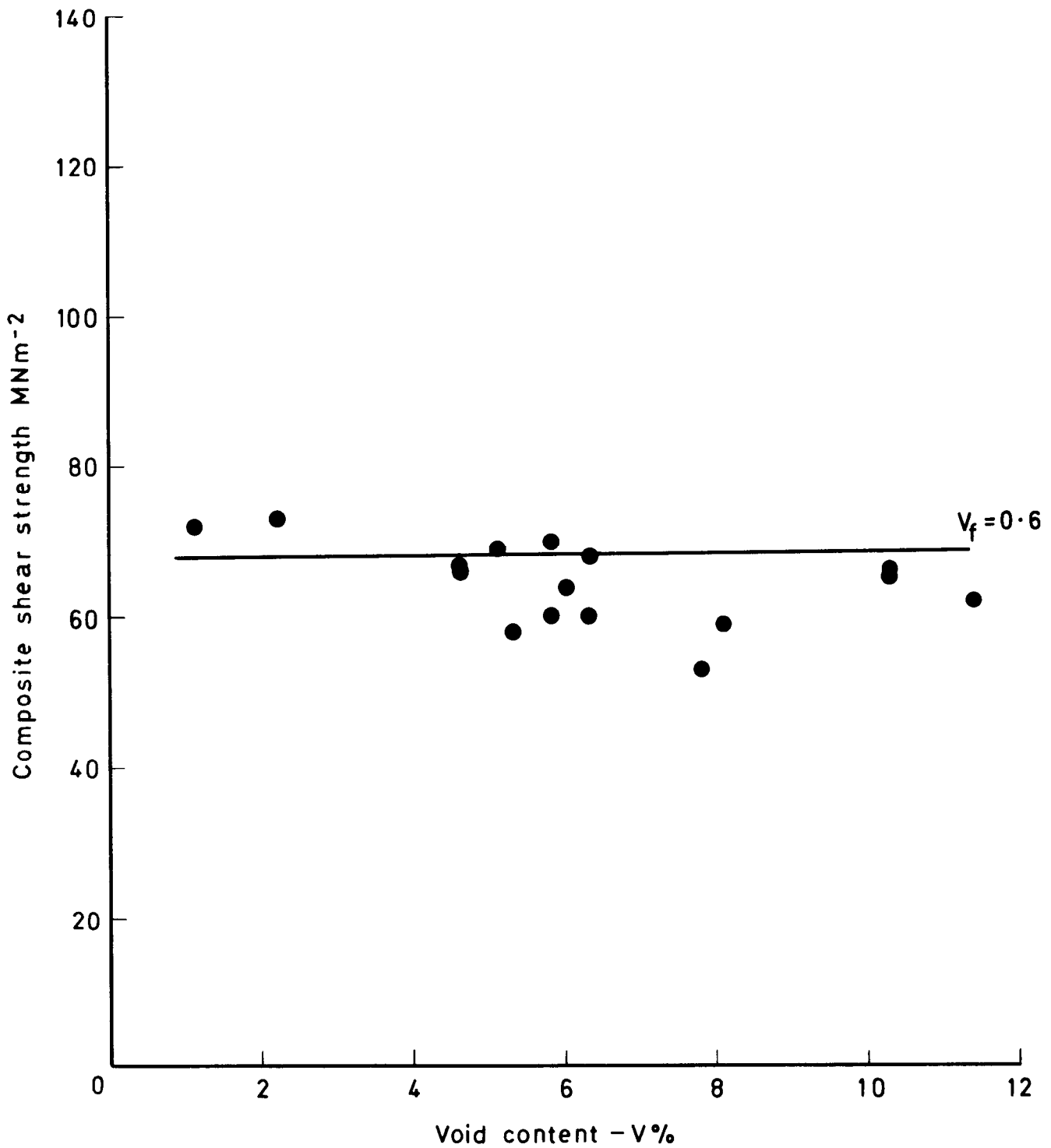
Fig. 39   Effect of voids on shear strength.
Rail — Type I
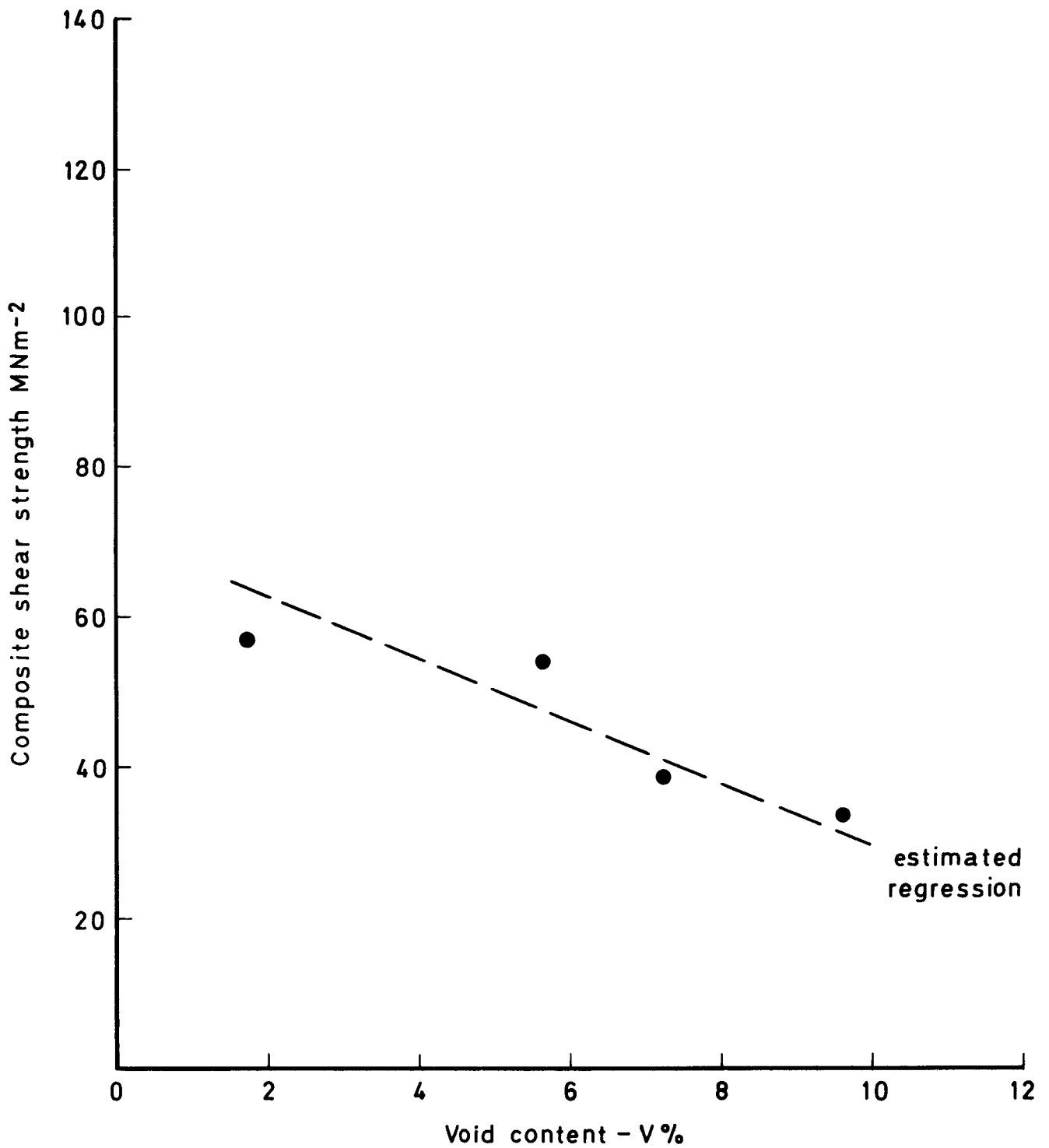
Fig. 40   Effect of voids on shear strength.
Short beam — Type I
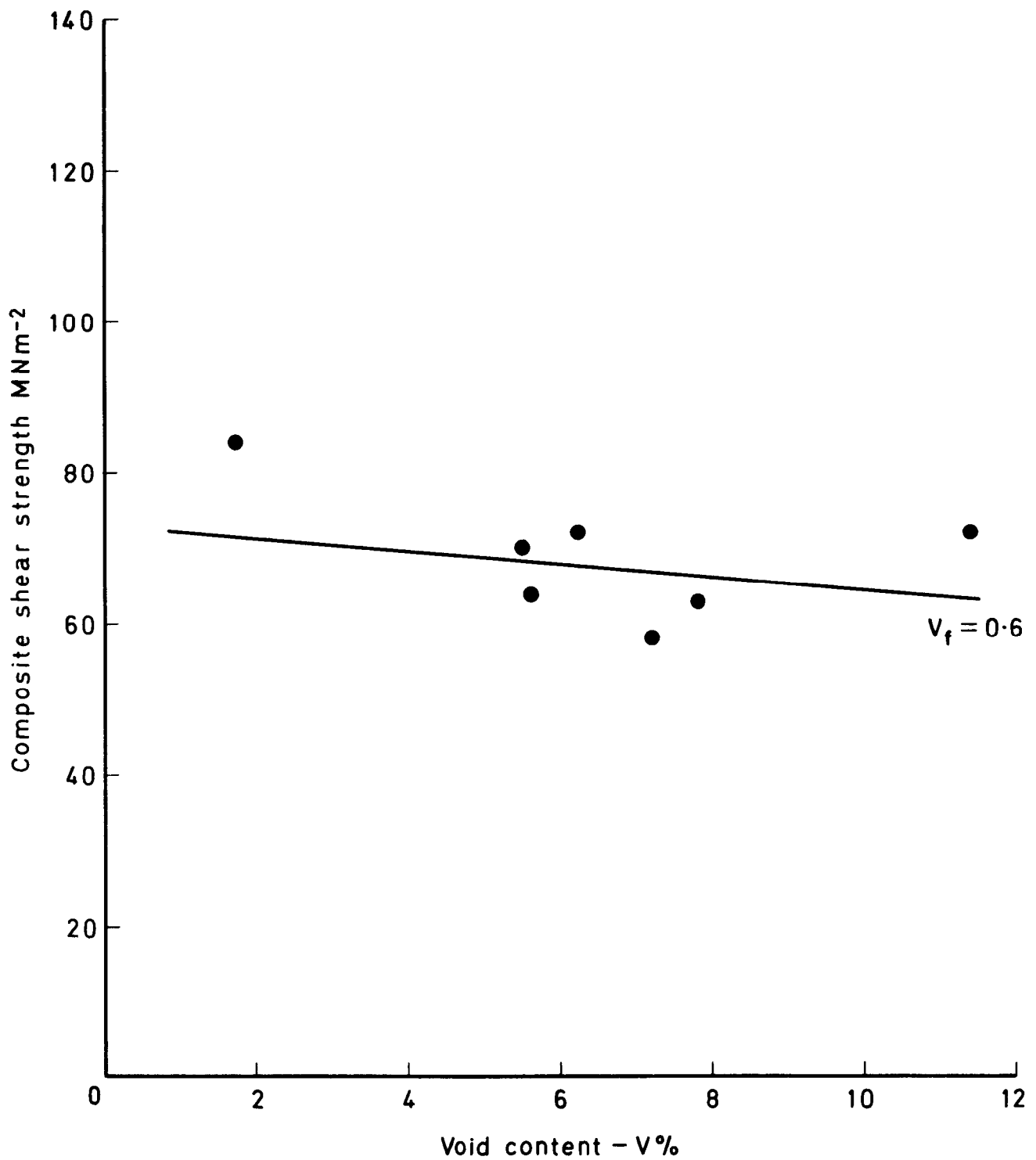
Fig. 41   Effect of voids on shear strength.
Transverse compression – Type I

Fig.42   Effect of voids on shear strength.
Rail —Type II

Fig.43   Effect of voids on shear strength.
Short beam — Type II

Fig. 44   Effect of voids on shear strength.
Transverse compression - Type II

Fig. 45   Variation of shear strength with fibre content. Type II