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DEPARTMENT OF SHIP SCIENCE

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THE MEASUREMENT OF STRUCTURAL PROPERTIES OF SAILCLOTH

by C. J. Satchwell Ph.D.

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Abstract

The report outlines a method of testing sailcloth to obtain elastic moduli and a proof stress appropriate to problems involving a single principal stress loading. Emphasis is given to practical problems, including a number of worked examples intended to help practitioners apply formulae. Standard uniaxial tensile test equipment is used, with the sole exception of an extensometer modification involving two dressmaking pins. Results for four popular sailcloths are presented.

Contents

Acknowledgements

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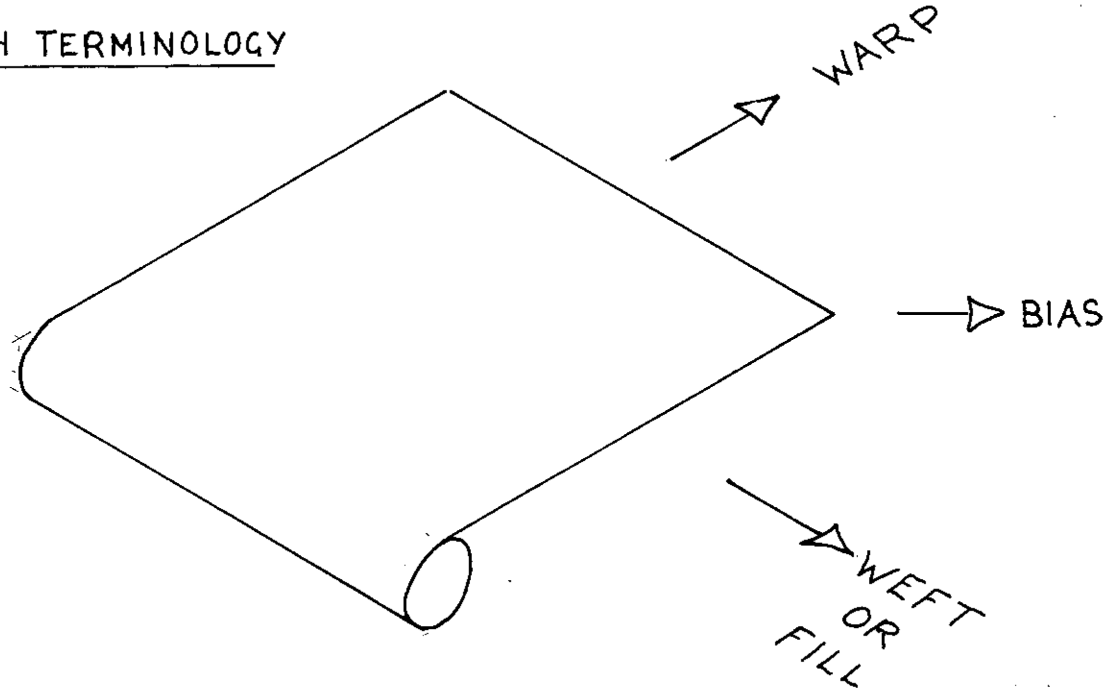
The Department of Ship Science, Southampton University
The Department of Civil Engineering, Southampton University
The Horizon group of sailmaking companies
The Wolfson Foundation
Howe and Bainbridge
Heathcoat Industrial Fabrics
The Science and Engineering Research Council

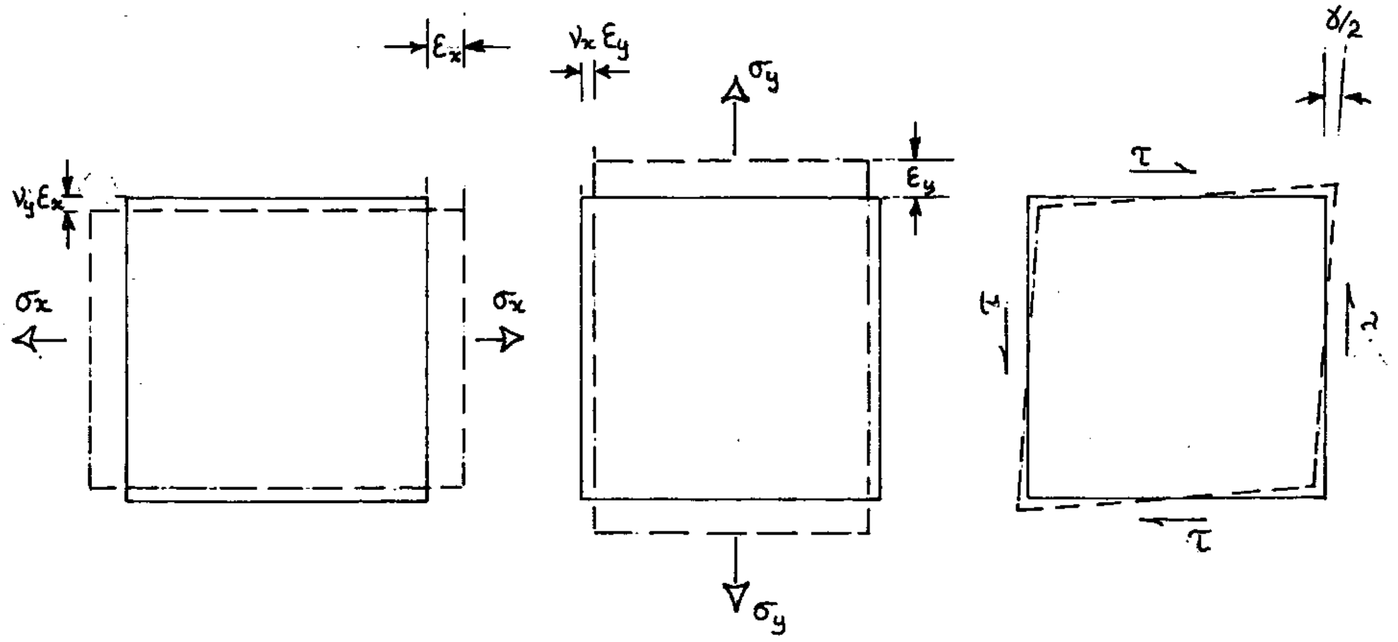
NOMENCLATURE

(1) CLOTH TERMINOLOGY



(2) CLOTH ELASTIC BEHAVIOUR

—— BEFORE LOAD
- - - AFTER LOAD



Nomenclature

Symbol	Name	Meaning
E	Young's Modulus	The ratio of direct strain to direct stress; for the linear part of a direct stress/direct strain curve; for uniaxial direct stress.
ν	Poisson's Ratio	The ratio of transverse contraction to direct extension; when a uniaxial direct stress is present; at a level below the elastic limit.
σ	Direct Stress	Force per unit width of a test specimen. (In common with other work on textiles, the thickness of a material is assumed to be invariant throughout the cloth). Stress may be defined in terms of force/distance rather than force/area.
τ	Shear stress	The intensity of shearing force tangential to a surface.
ε	Direct strain	Change in length of an element/Original length of an element.
γ	Shear strain	The deviation from a right angle of warp/weft yarns.
G	Shear Modulus	The ratio of shear stress/shear strain within the elastic limit; for cloth subjected to pure shear.

Suffixes:

x - weft direction
y - warp direction

Further background: refs (2) and (3).

Introduction

Most sailcloth structural testing is orientated either towards quality control or providing sailmakers with an indication of 'stiff' or 'soft' directions within a material. In recent years, new structural methods have been developed to determine the stresses in sails e.g. ref. (1) et al. This has created a need for better test methods.

The present work follows a request from the Horizon group of sailmaking companies to develop test methods, to produce quantifiable structural properties, to enable structural calculations to be used in sail design.

Specific aims are to determine elastic moduli for sailcloth and to provide an indication of the maximum advisable stress that a material can carry. Implicit in those aims is the idea that the region of interest lies beneath a stress value that results in a breakdown of resin/yarn adhesion. No account is taken of deterioration of cloth due to weathering or flogging and it should be appreciated that these effects are detrimental to structural properties. The general methodology described in this report could be equally well applied to specimens which have been subjected to a specified amount of weather or mechanical manipulation. Any modification to structural properties would then indicate changes from those causes.

Throughout the report, the emphasis is on 'how to do it' rather than the finer points of structural theory. This responds to a demand for a usable answer obtained quickly, but it should be appreciated that more rigorous methods could be developed at the expense of more time and equipment. All graphs use the ordinate (conventional y axis) for strain and the abscissa (conventional x axis) for stress. This is the convention currently used by weavers and is retained because much of their tensile test equipment cannot produce 'correct' plots of stress on the ordinate and strain on the abscissa.

It should also be noted that these techniques can be used for other linear anisotropic materials although careful checking of background assumptions is recommended before application. To aid this process a number of relevant comments are made in appropriate places in the report.

1. Background to Load-Extension curves and related structural concepts

Physical processes involved in sailcloth extension need to be related to a load-extension curve in order to establish the maximum advisable stress. What follows is a consensus reached at a meeting between weavers' representatives and the author at Southampton University on 21st June 1984. This is a generalisation and may be inappropriate for possible future sailcloths. It is therefore recommended that a similar appraisal of relevant physical processes be made before applying the proposed model to materials which are not of resinated polyester construction.

General characteristics of a sailcloth load-extension curve are shown in Fig. 1. Physical processes involved are also indicated. As load is applied, a fairly linear stress/strain relationship is initially found. This corresponds to yarn extension, possibly crimp interchange and also resin extension. As further load is applied, resin/yarn bonds begin to break in a progressive fashion, followed ultimately by the failure of the specimen.

One particular point of interest is point 'A' on the curve. This is where resin breakdown begins. Below this point, repeated application and relaxation of load does not affect structural properties. It is analogous to a 'yield point' or 'elastic limit', which can be identified in metal testing. In sailcloth, it represents a point where further application of load implies a permanent change in material properties.

GENERAL CHARACTERISTICS AND PHYSICAL SIGNIFICANCE OF SAILCLOTH LOAD-EXTENSION GRAPHS

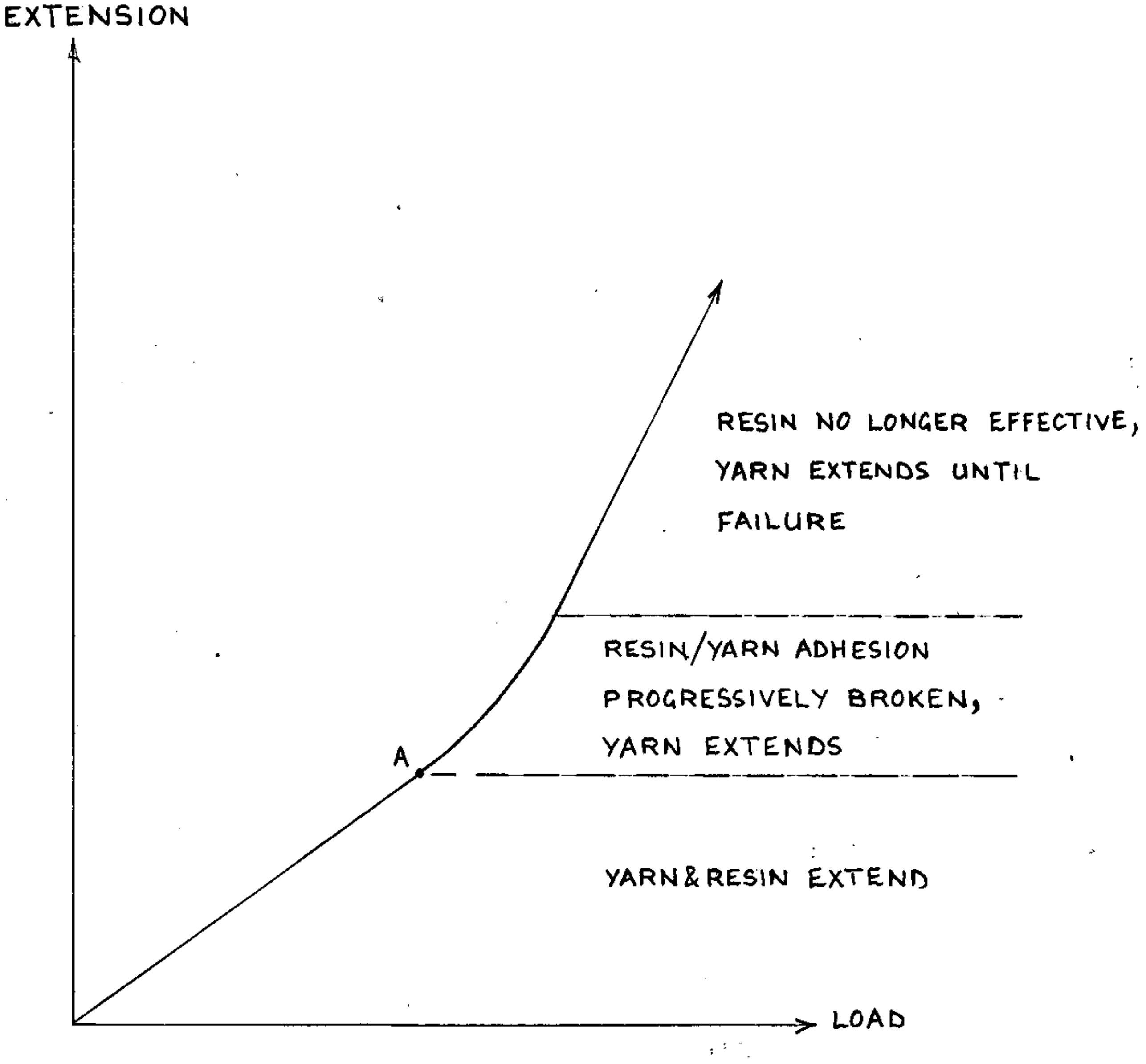


Fig 1

Point 'A' cannot be readily identified, as resin breakdown is progressive and the change from linear to non-linear parts of the curve is very gradual. A similar problem exists with some metals (e.g. aluminium) and to overcome it a 'proof stress' concept is used. The usefulness of the proof stress concept is that it provides a guide to working stress levels of a particular material. In metals, the proof stress is usually defined as the stress required to produce a .1% permanent strain in the material after removal of load. This is illustrated in Fig. 2a and will be referred to later, in the context of a maximum advisable stress for sailcloth (see section 3).

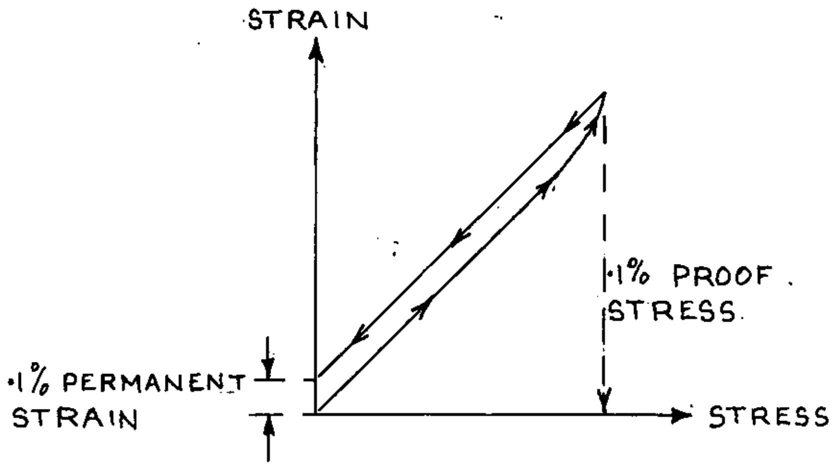
One major difference between sailcloth and metals relates to the variation of properties caused by loss of resin adhesion. This loss may vary throughout a sail as some parts 'flog' more than others and are also subject to varying amounts of chafe. Realistically therefore, any final choice of maximum advisable stress must rest with an individual sail designer; who alone can assess the probability of resin damage and make appropriate corrections. This will be manifest in the safety factor on the proof stress.

In considering practical tests in a laboratory the tensile test machine jaw effects can be a problem with very short specimens. The St. Venant principle (ref. 3) indicates that a short distance away from a jaw, stresses are essentially independent of jaw details. With long, thin specimens, jaw effects can usually be ignored.

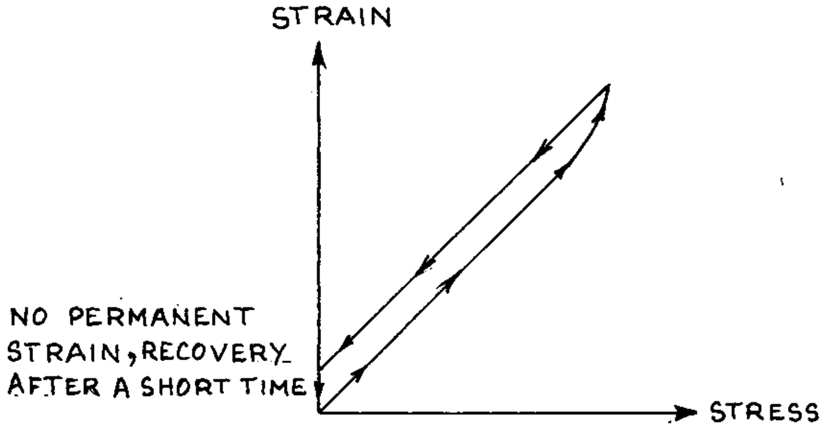
Other results (ref. 3) may be combined with the St. Venant principle to demonstrate that over the middle length of a specimen, stresses are essentially uniform across the width.

'PROOF STRESS' CONCEPT IN STRUCTURAL TESTING

a. Metals



b. Sailcloth Stress-Strain Curve



c. 'Proof Stress' Concept Applied to Sailcloth

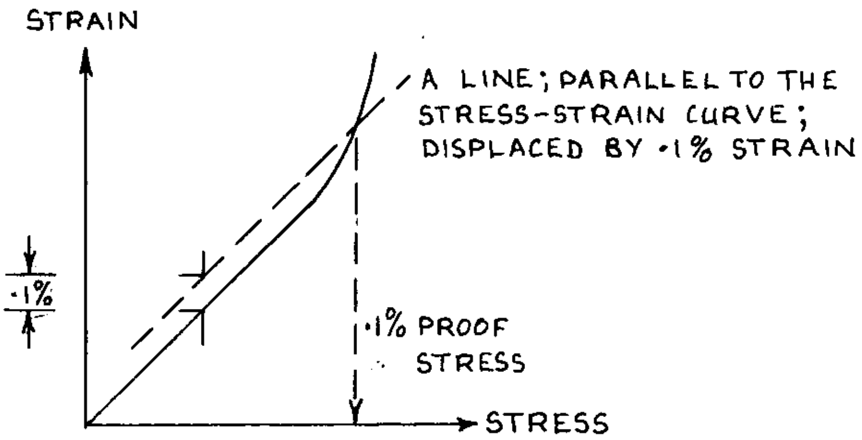


Fig 2

2. Background to Sailcloth Elasticity

Sailcloth elasticity can be expressed in terms of familiar elastic constants such as Young's Moduli, Poisson's Ratios and a shear modulus. Background research on this is published in ref. (1) and the essential equations are:

$$\varepsilon x = \frac{\sigma x}{Ex} - \frac{\nu x}{Ey}\sigma y \qquad 1.$$

$$\varepsilon y = \frac{\sigma y}{Ey} - \frac{\nu y}{Ex}\sigma x \qquad 2.$$

$$\gamma = \frac{\tau}{G} \qquad 3.$$

This particular theory has some shortcomings as it contains one constant too many to give consistent results in structural calculations (it violates the Maxwell-Betti criteria). Background to this problem is given in ref (1) along with sailcloth elasticity relationships that can be used in structural calculations. For a material to be structurally 'linear'

$$\frac{\nu x}{Ey} = \frac{\nu y}{Ex} = \lambda \qquad 4.$$

and the essential structural equations are:

$$\varepsilon x = \frac{\sigma x}{Ex} - \lambda\sigma y \qquad 5.$$

$$\varepsilon y = \frac{\sigma y}{Ey} - \lambda\sigma x \qquad 6.$$

$$\gamma = \frac{\tau}{G} \qquad 7.$$

The quantities Ex, Ey, λ and G are required from tests to enable structural calculations to be performed.

3. Considerations behind test procedures

Essential aims of the test procedures are:

(1) To obtain elastic constants Ex, Ey, λ and G (equations 4-7).
(2) To assess an upper bound for the maximum advisable stress.
(3) To devise procedures which can be applied easily and routinely, based on widely-available tensile test equipment.

Work already carried out ref(1) had some similar objectives and used mostly standard tensile test equipment in conjunction with warp, weft and bias specimens. The same equipment and general methodology can also be used to include the requirement for obtaining an upper bound to the maximum advisable stress level.

General Principles for obtaining Elastic Moduli:

Warp and weft specimens are loaded uniaxially and observations made of direct stress, direct strain and Poisson (lateral) strain. Below the elastic limit, Young's Modulus is direct stress/direct strain and Poisson's Ratio is lateral strain/ direct strain with positive lateral strain in the sense of a contraction.

The shear modulus is harder to obtain. When a bias specimen is tested in a similar manner to the weft/warp specimens, both direct and shear strains are induced. If the bias specimen direct stress and direct strain are noted, then with some mathematics it is possible to remove the direct-stress effects from the observations and obtain shear stress and shear strain. Shear modulus is then shear stress/shear strain within the limits of the definition.

General Principles for an upper limit of maximum advisable stress:

Mention has already been made of the 'proof stress' concept in metal testing. Sailcloth does not behave like metal. After slight over-extension it can recover its original dimensions. This effect can be seen from Fig. 2b. When stress is applied a sailcloth load/extension curve is much the same as that of metal. After small over-extension there is no permanent set. There may be a temporary set but within a reasonable period of time (typically less than one hour) the original length is restored. This ability to recover the original dimensions is called 'recovery'. Nevertheless the 'proof stress' concept may still be applied with a slightly modified definition.

When a stress-strain curve is obtained, the .1% proof stress may be redefined as: "the stress corresponding to the intersection of the stress/strain curve, with a straight line, parallel to the linear part of the stress/strain curve, but offset by a positive strain of .1%". (Reference should be made to Fig. 2c for clarification).

It must be pointed out that this method of assessing maximum advisable stress takes no account of interactions between different stresses. For example, assessment of maximum advisable weft stress is made without warp or shear stress present. When these other stresses are present, resin strains may be greater and maximum advisable weft stress less.

Similarly, assessment of maximum advisable shear stress from a bias specimen test result may be too small, owing to the presence of warp and weft stresses generated by the test. The relative magnitudes of warp, weft and shear stresses may be found directly from a Mohr's circle calculation, as described in ref. (2).

To satisfy these objections, a series of tests with various interaction stresses present should be carried out to obtain an envelope of maximum advisable stresses. However, in the interests of keeping the work within manageable proportions it is initially proposed to ignore stress interactions and proceed with simple tensile tests on warp, weft and bias specimens. The interpretation should be confined to problems with essentially a uniaxial loading, such as stresses at the clew of a genoa.

It should be appreciated also that a general problem involving two principal stresses of arbitrary orientation and magnitude cannot be directly related to the proposed test methods.

Other points:

1) In order to obtain the maximum advisable stress, specimens need to be over-stretched, resulting in permanent damage to structural properties. To obtain both direct and Poisson strains, the same specimen may need to be tested twice if the equipment cannot plot both sets of strain simultaneously. To reconcile these factors, it is proposed that the specimen be extended within the linear range (say direct strain limits of .5 - .75%), the stress noted, and then a Poisson strain test done without exceeding that stress level. Thereafter, the tensile test equipment can be re-set for direct strain measurement and the specimen pulled beyond the point of resin breakdown.

2) Misalignments in mounting sailcloth within a tensile test machine often result in strange curves at low stresses. Results should be assessed at higher stress levels, where 'mounting' errors are absent. Fig. 6c is one example of this.

4. Apparatus

Test apparatus consisted of an Instron 1195 tensile test machine with a compatible extensometer. The extensometer was fitted with two pins rather than knife edges. Otherwise, all equipment was standard.

Sailcloth specimens (50mm x 400mm) were accurately cut in warp, weft and bias directions. Specimens were cut in a 'fan', centred on a point 150mm from the edge of the cloth.

Specimens were carefully mounted in 50mm jaws and extensometer pins pushed through. A backplate was present to ensure the sailcloth remained flat whilst the pins were inserted. The backplate was then removed and the apparatus ready for testing sailcloth.

5. Test Procedures

General Points

Equipment available could not simultaneously measure direct and Poisson strains, so some preliminary testing was needed to establish safe stress levels for a Poisson test.

All tests were carried out using an extensometer attached directly to the specimen for length measurement and inbuilt sensors for force measurement. Strains were calculated as extension/extensometer length and stresses as force/specimen width.

Test details

Warp or weft specimen:

(1) Initially the specimen was pulled and direct strain measured within the direct strain range 0 - .5%. This gave an indication of a safe stress level for the Poisson Test.

(2) The specimen was pulled and Poisson strains measured up to the stress level indicated by test (1). This enabled Poisson strains to be related to stress and later to direct strains so that a Poisson's ratio could be established.

(3) Finally the specimen was pulled well beyond its elastic limit and direct strains measured. This test completed the information needed for Poisson's ratio as well as giving information required for the Young's Modulus and proof stress limit of the specimen.

Bias specimen:

The specimen was pulled well beyond the linear range of the load/extension graph and measurements made of direct strains and direct stresses. This test provided information to assess the shear modulus and shear proof stress for the material.

6. Interpretation of Results

Test results are obtained as a series of stress/strain graphs from which elastic moduli and proof stress limits need to be extracted. A number of worked examples are given in Figs. 3-6 in order to aid interpretation of the following text.

Warp and Weft Specimens:

At the start of the curves, gradients may be a little eratic owing to 'mounting' errors. Generally, for direct strain measurements, the minimum linear gradient is used as a basis for both proof stress and Young's Modulus, below resin breakdown point.

Young's Modulus is direct stress/direct strain or the inverse of the minimum linear gradient for a direct strain v. direct stress curve.

Proof stress is the stress at the intersection of the direct strain v. direct stress curve and a straight line, parallel to the minimum linear gradient but displaced away from it by .1% strain.

Poisson's ratio is the ratio of transverse contraction to longitudinal extension. For a given stress increment in the correct part of the curve (i.e. away from regions of mounting errors or resin breakdown).this amounts to Poisson strain/direct strain.

Ratios of $^{\nu x}/Ey$ and $^{\nu y}/Ex$ can be formed and checked to see if the equality of equation 4 is satisfied. Where it is not, it is often necessary to linearize structural properties for calculation purposes. The usual method is to obtain the geometric average with $\lambda=(^{\nu x}/Ey + {}^{\nu y}/Ex)/2$.

Bias Specimens:

It was noted previously that a bias specimen test includes the effects of warp and weft stresses as well as shear and that some analysis would be needed to obtain shear modulus and shear proof stress. This analysis is developed using the assumption that equations 1, 2 and 3 alone describe the elastic behaviour of the specimen. Stress and strain transformation equations from refs (1) and (2) are used to relate a weft/warp axis system to a transposed axis system orientated on the bias. If σ and ε denote bias specimen direct stress and direct strain then from ref (1)

$$\sigma x = \sigma/2 \qquad 8.$$

$$\sigma y = \sigma/2 \qquad 9.$$

$$\tau = \sigma/2 \qquad 10.$$

$$\varepsilon = \{\varepsilon x+\varepsilon y+\gamma\}/2 \qquad 11.$$

$$\gamma = 2\varepsilon - \varepsilon x - \varepsilon y \qquad 12.$$

$$G = \tau/\gamma = \sigma/(4\varepsilon - \sigma\{1/Ex + 1/Ey - \nu y/Ex - \nu x/Ey\}) \qquad 13.$$

Now equation 13. allows the shear modulus to be found if Young's Moduli and Poisson's ratios are available for the material. In practice, the procedure is to establish the minimum gradient on the graph, then select a stress increment ($\Delta\sigma$), read the strain increment ($\Delta\varepsilon$) and apply equation 13. as:

$$G=\Delta\sigma/(4\Delta\sigma\{1/Ex + 1/Ey - \nu y/Ex-\nu x/Ey\}) \qquad 14.$$

Young's Moduli and Poisson's ratios are available from tests on warp and weft specimens.

The proof shear stress limit may be found by a similar indirect method. Firstly the bias strain corresponding to a .1% shear strain needs to be found. Combining equations 1-3, 8-11 and adopting incremental (Δ) notation gives:

$$\Delta\varepsilon = \Delta\sigma(1/Ex + 1/Ey - \nu y/Ex-\nu x/Ey + 1/G)/4 \qquad 15.$$

A .1% incremental shear strain occurs when:

$$\Delta\tau/G = \Delta\sigma/2G = .001$$

whence $\Delta\sigma = .002G$ 16.

If equation 16. is substituted into equation 15.

$$\Delta\varepsilon = .001G(1/Ex + 1/Ey - \nu y/Ex - \nu x/Ey + 1/G)/2 \qquad 17.$$

Now equation 17. gives the bias strain corresponding to a .1% shear strain and indicates by how far a line, parallel to the bias direct strain v. stress curve, must be offset in order to obtain the .1% proof shear stress for the material.

Proof shear stress is therefore obtained by the following method:

a) Calculate $\Delta\varepsilon$ from equation 17.

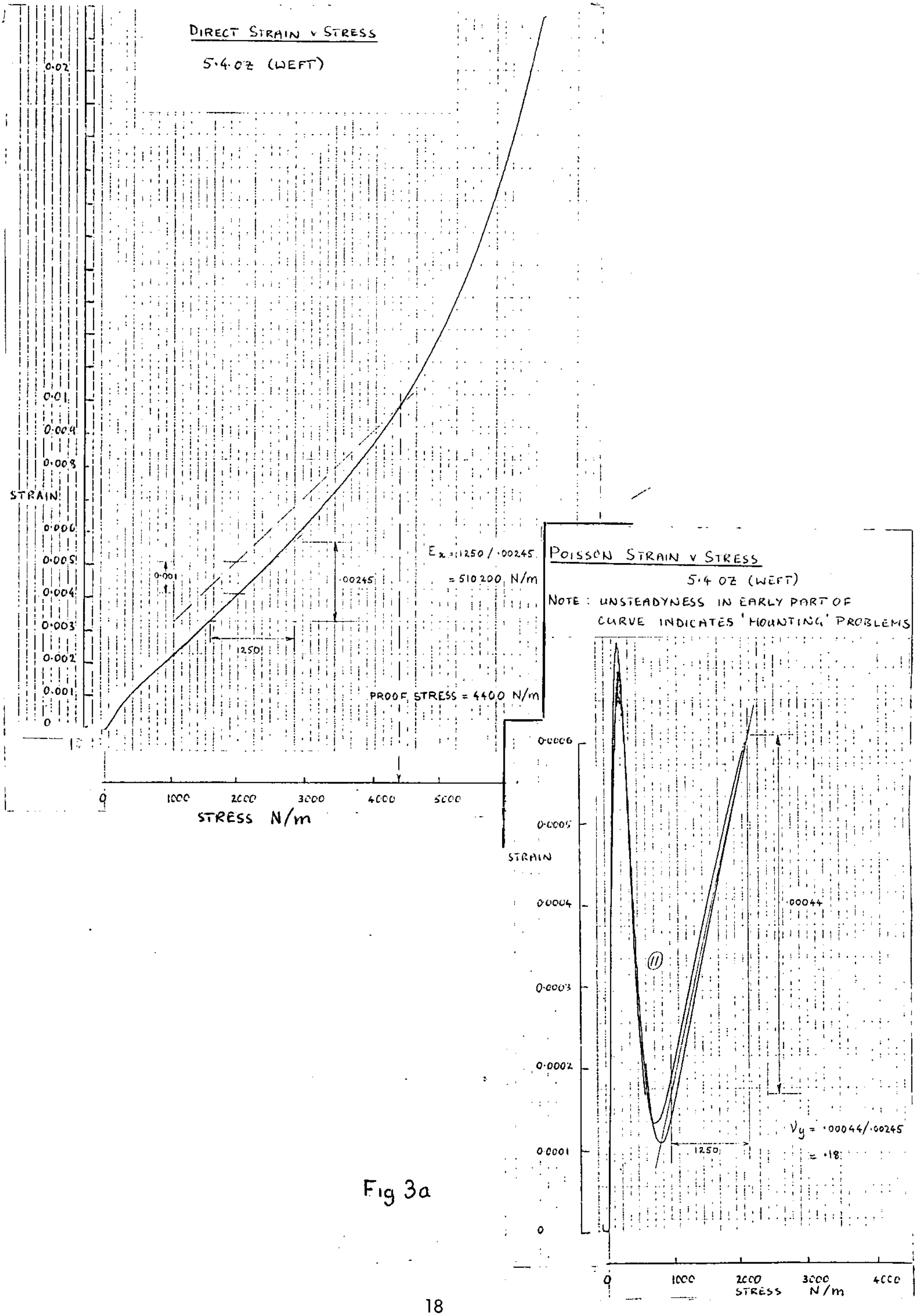
b) Draw a straight line, parallel to the 'minimum gradient' section of the bias direct strain v. direct stress curve, but displaced from it by a strain of $\Delta\varepsilon$, calculated from equation 17 (see for example Fig. 6c).

c) Note the point of intersection and read off the bias direct stress.

d) The proof shear stress is half the proof bias stress (from equation 10.). One very important assumption is implicit in the method. It is assumed that proof warp and weft stresses will not be exceeded before the bias specimen reaches its proof shear stress. If there is any doubt as to whether that is the case, warp and weft stresses may be checked using equations 8. and 9. In general shear proof stress will be reached first, but if not, this method becomes inaccurate.

Worked examples:

Worked examples are given in Figs. 3-6. Results from these examples are shown in Table I. The worked examples apply the principles outlined in the previous section. The order of the calculations is νx, Ex, weft proof stress, νy, Ey, warp proof stress, G, bias strain for .1% shear strain and shear proof stress. Essentially, Ex, νy, Ey, νx must all be obtained before G, which must be followed by the bias strain for .1% shear strain and shear proof stress.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5·4 oz (WEFT)
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
STRAIN
0·001
·00245
1250
Ex = 1250 / ·00245
= 510200 N/m
PROOF STRESS = 4400 N/m
0
1000
2000
3000
4000
5000
STRESS N/m
POISSON STRAIN v STRESS
5·4 oz (WEFT)
NOTE : UNSTEADYNESS IN EARLY PART OF CURVE INDICATES 'MOUNTING' PROBLEMS
0·0006
0·0005
STRAIN
0·0004
0·0003
0·0002
0·0001
0
⑪
·00044
1250
Vy = ·00044/·00245
= ·18
0
1000
2000
3000
4000
STRESS N/m

Fig 3a

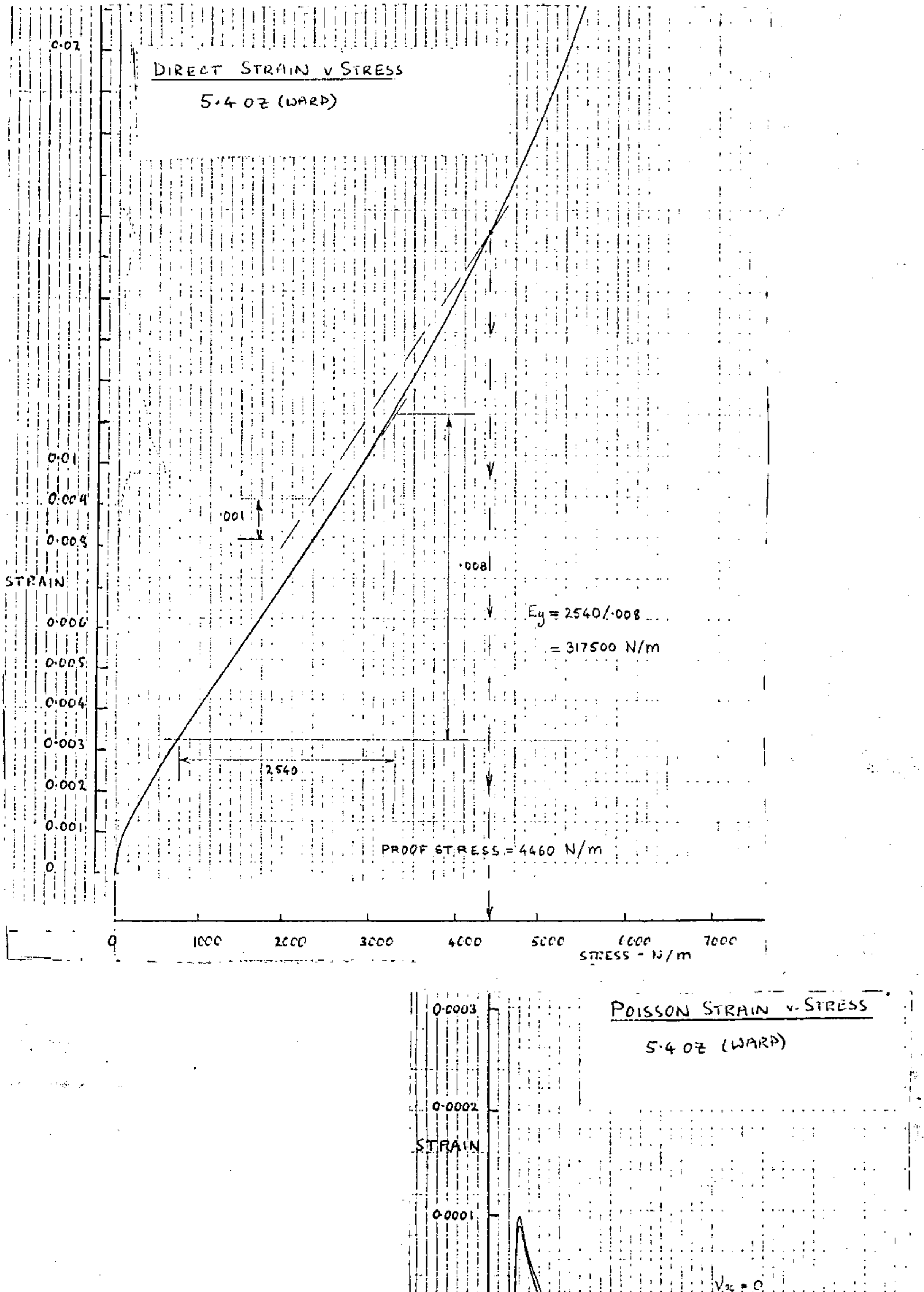

DIRECT STRAIN v STRESS
5·4 oz (WARP)
STRAIN
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
·001
·008
2540
Ey = 2540/·008
= 317500 N/m
PROOF STRESS = 4460 N/m
0
1000
2000
3000
4000
5000
6000
7000
STRESS - N/m
POISSON STRAIN v STRESS
5·4 oz (WARP)
STRAIN
0·0003
0·0002
0·0001
0
Vx = 0
0
1000
2000
3000
4000
STRESS N/m

Fig 3b

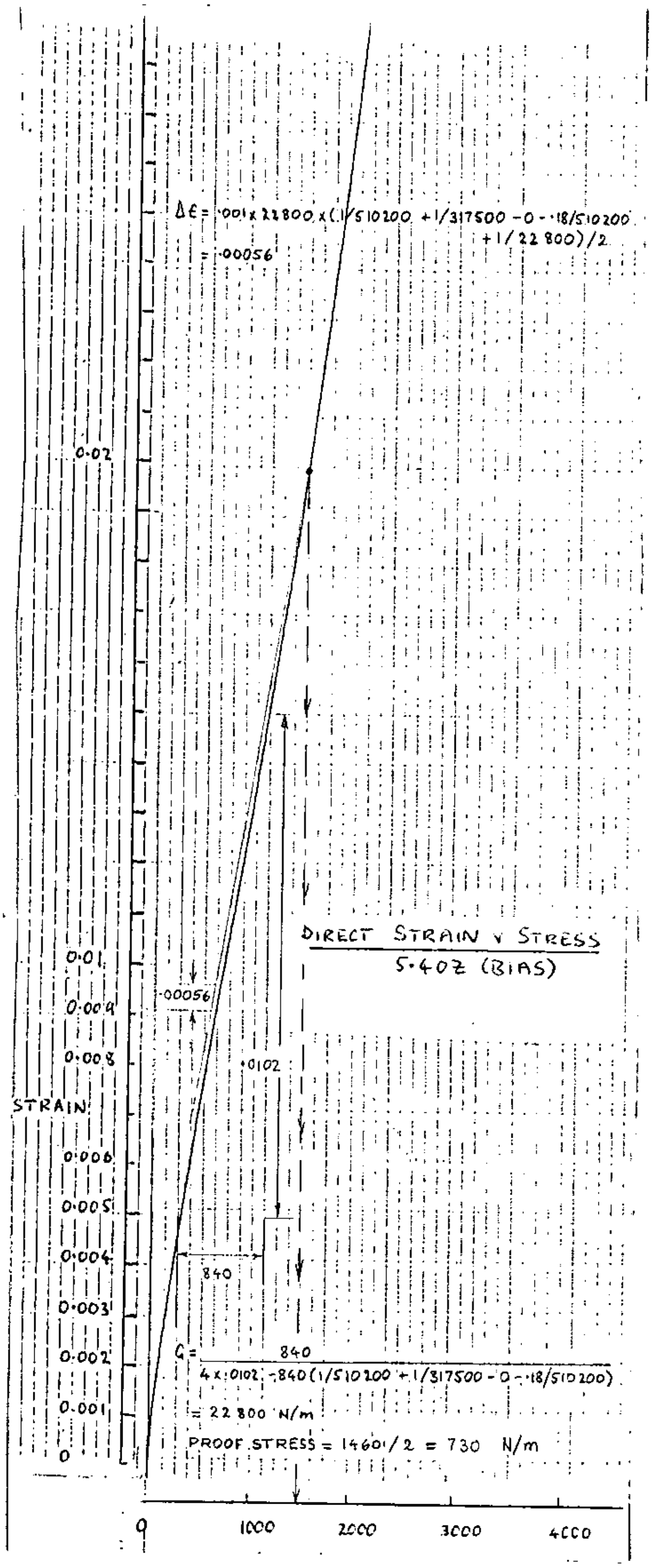

Δε = ·001 x 22800 x (·1/510200 +1/317500 −0 −·18/510200 +1/22 800)/2
= ·00056
0·02
DIRECT STRAIN v STRESS
5·4oz (BIAS)
0·01
·00056
0·009
0·008
·0102
STRAIN
0·006
0·005
0·004
840
0·003
0·002
0·001
0
G = 840 / (4 x ·0102 −840(1/510200 +1/317500 − 0 − ·18/510200))
= 22 800 N/m
PROOF STRESS = 1460/2 = 730 N/m
0
1000
2000
3000
4000

Fig 3c

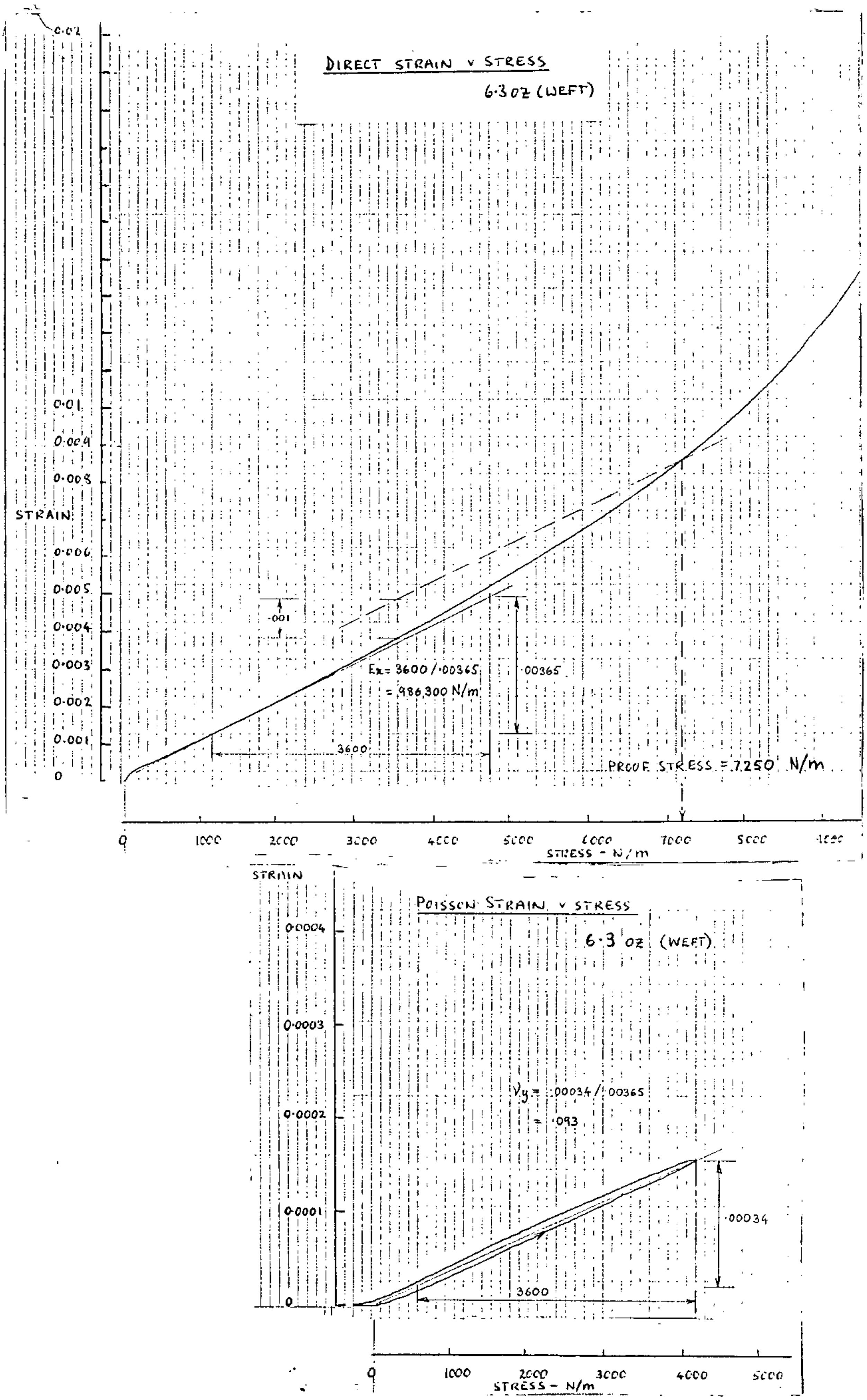

DIRECT STRAIN v STRESS
6·3 oz (WEFT)
STRAIN
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
·001
Ex = 3600 / ·00365
= 986,300 N/m
·00365
3600
PROOF STRESS = 7250 N/m
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
STRESS - N/m
STRAIN
POISSON STRAIN v STRESS
6·3 oz (WEFT)
0·0004
0·0003
0·0002
0·0001
0
νy = ·00034 / ·00365
= ·093
·00034
3600
0
1000
2000
3000
4000
5000
STRESS - N/m

Fig 4a

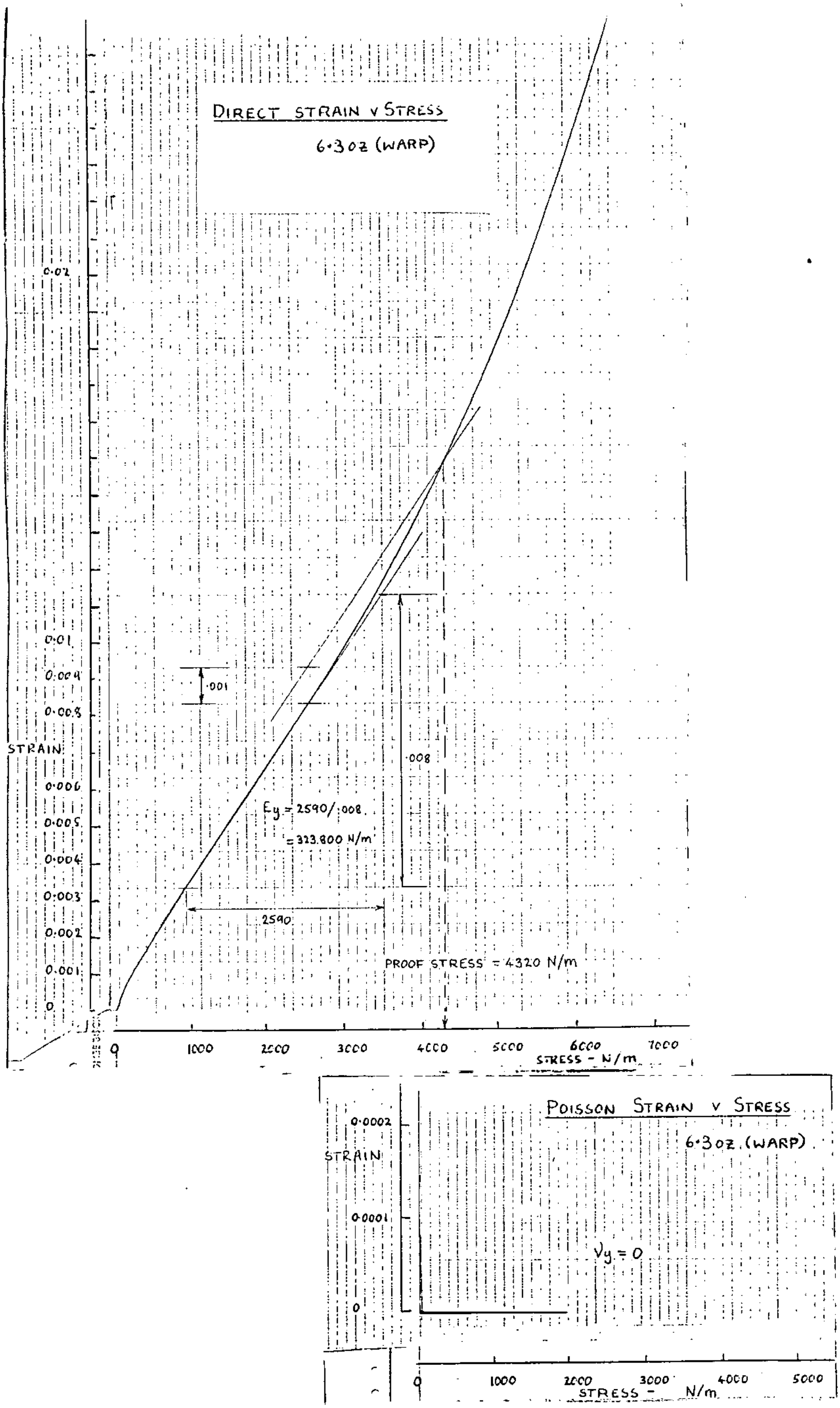

DIRECT STRAIN v STRESS
6·3oz (WARP)
STRAIN
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
·001
·008
Ey = 2590/·008
= 323.800 N/m
2590
PROOF STRESS = 4320 N/m
0
1000
2000
3000
4000
5000
6000
7000
STRESS - N/m
POISSON STRAIN v STRESS
6·3oz (WARP)
STRAIN
0·0002
0·0001
0
Vy = 0
0
1000
2000
3000
4000
5000
STRESS - N/m

Fig 4b

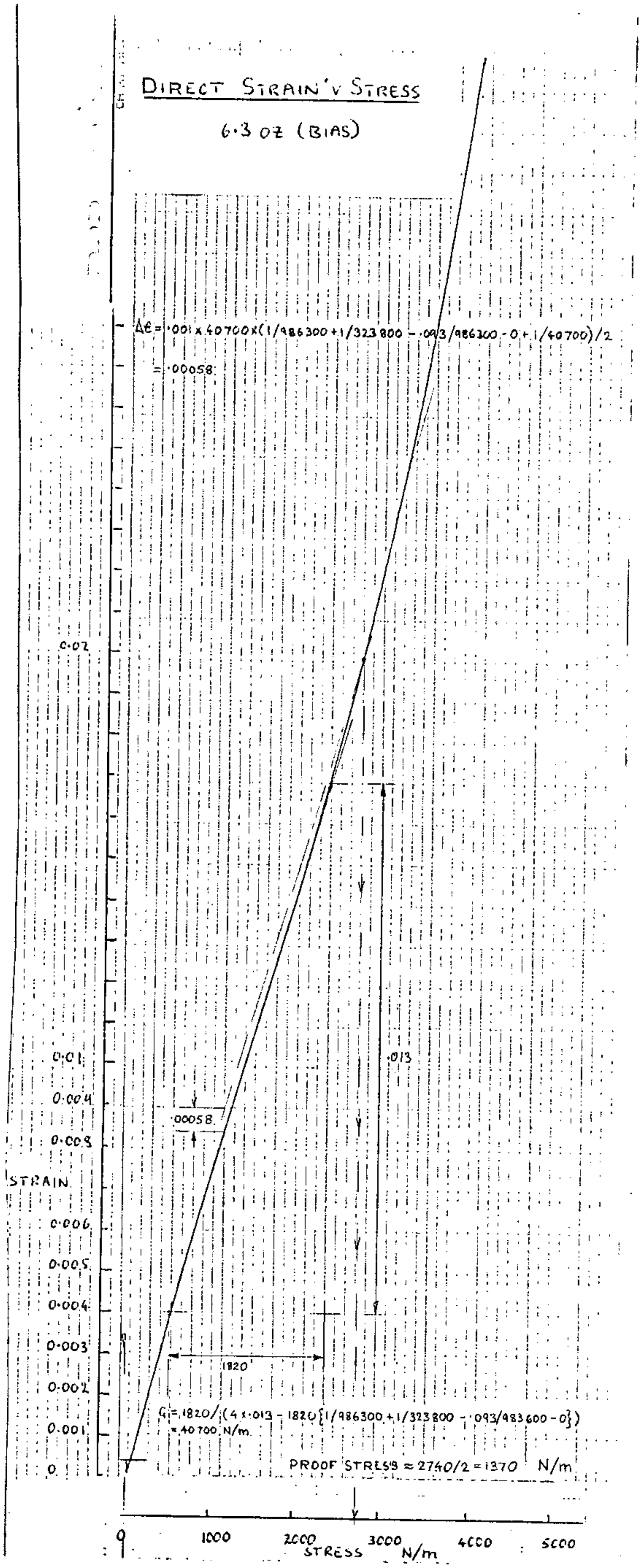
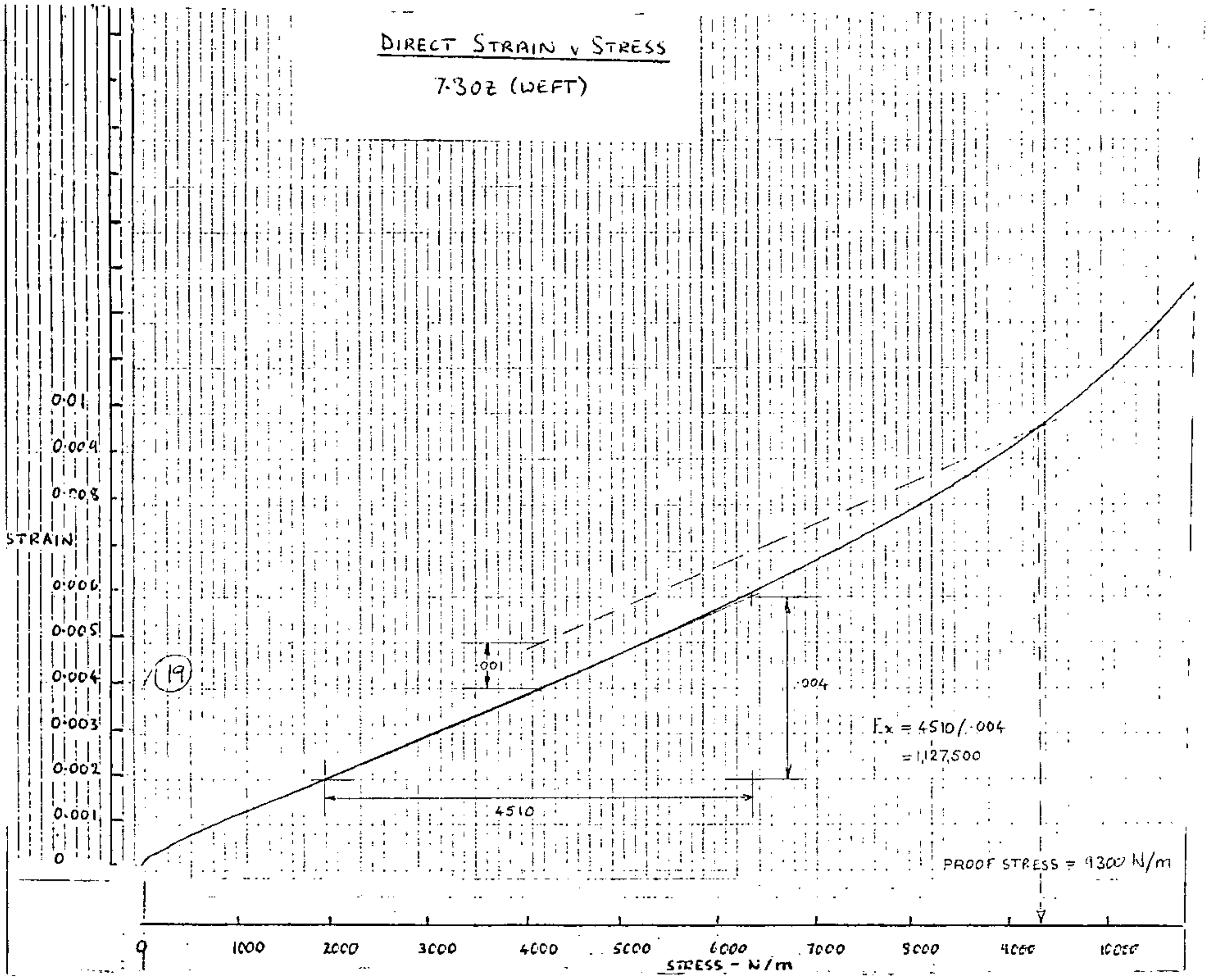

DIRECT STRAIN v STRESS
6·3 oz (BIAS)
Δε = ·001 x 40700 x (1/986300 + 1/323800 - ·093/986300 - 0 + 1/40700)/2
= ·00058
0·02
0·01
0·004
0·008
STRAIN
0·006
0·005
0·004
0·003
0·002
0·001
0
·00058
·013
1820
G = 1820/(4 x ·013 - 1820{1/986300 + 1/323800 - ·093/983600 - 0})
= 40700 N/m
PROOF STRESS ≈ 2740/2 = 1370 N/m
0
1000
2000
3000
4000
5000
STRESS N/m

Fig 4c


DIRECT STRAIN v STRESS
7·3oz (WEFT)
STRAIN
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
(19)
·001
·004
Ex = 4510/·004
= 1,127,500
4510
PROOF STRESS = 9300 N/m
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
STRESS – N/m

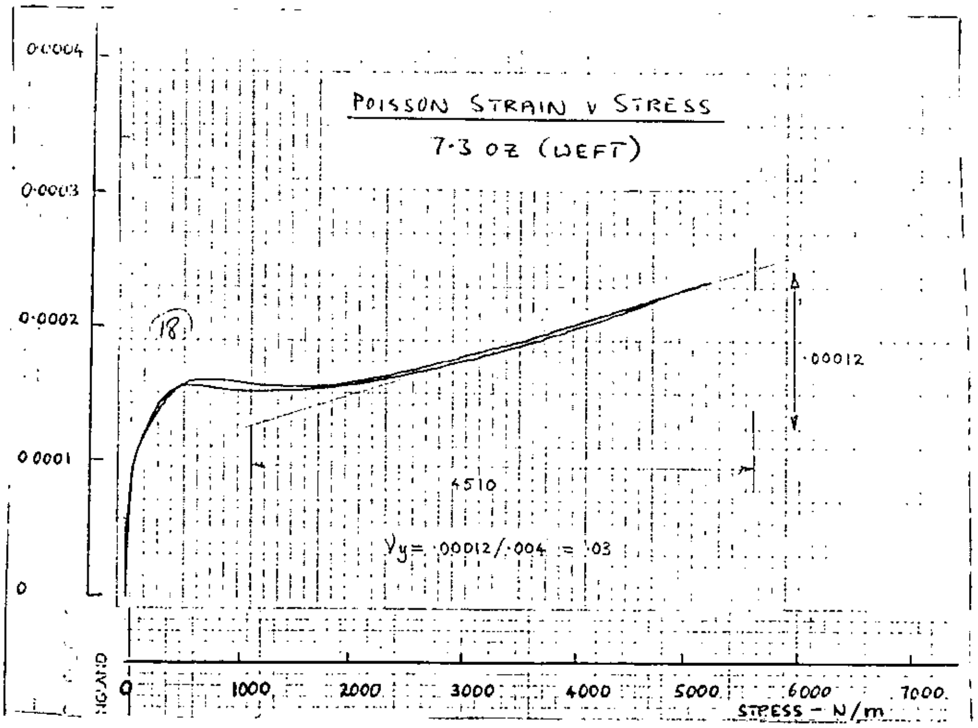

POISSON STRAIN v STRESS
7·3 oz (WEFT)
0·0004
0·0003
0·0002
0·0001
0
(18)
·00012
4510
Vy = ·00012/·004 = ·03
0
1000
2000
3000
4000
5000
6000
7000
STRESS – N/m

Fig 5a

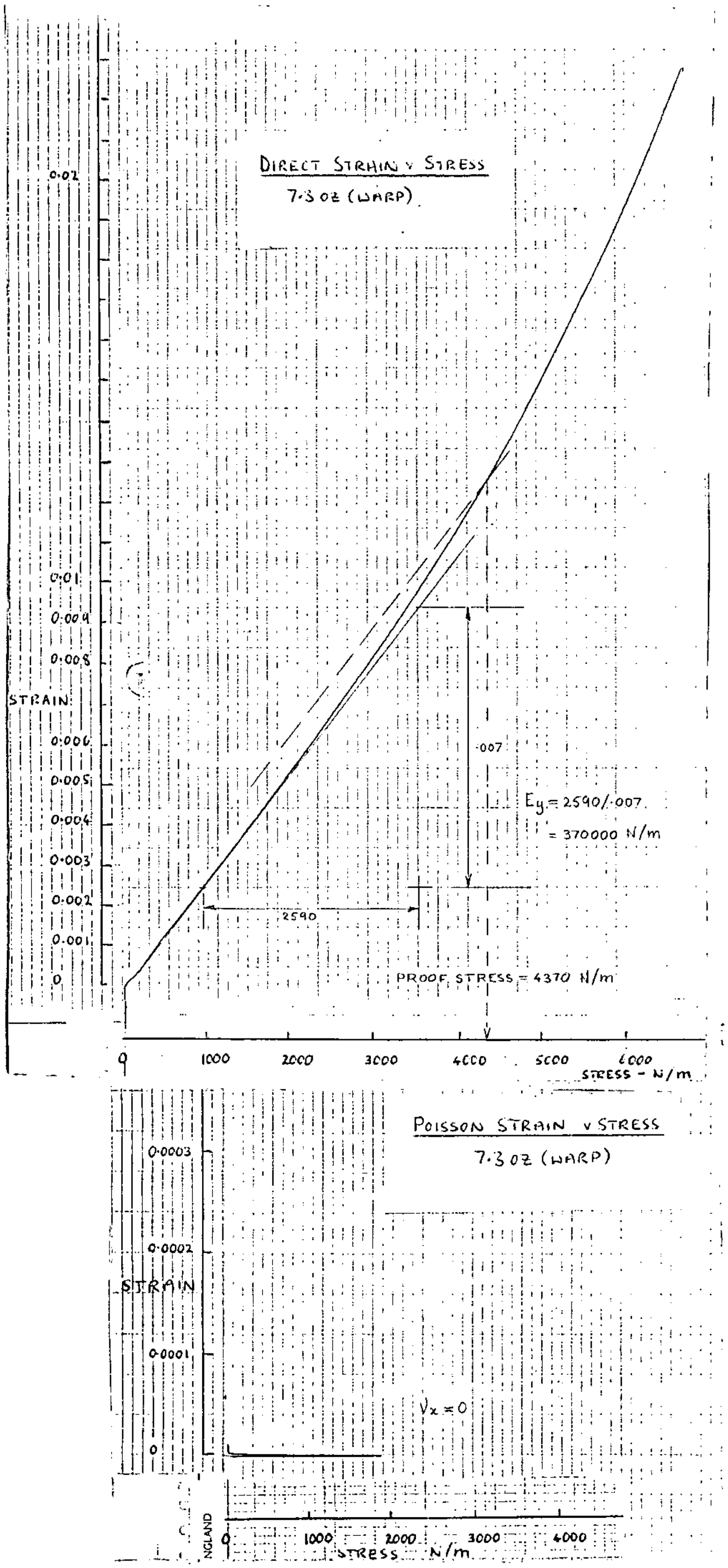

DIRECT STRAIN v STRESS
7·3 oz (WARP)
STRAIN
0.02
0.01
0.009
0.008
0.006
0.005
0.004
0.003
0.002
0.001
0
·007
Ey = 2590/·007
= 370000 N/m
2590
PROOF STRESS = 4370 N/m
0
1000
2000
3000
4000
5000
6000
STRESS - N/m
POISSON STRAIN v STRESS
7·3 oz (WARP)
STRAIN
0·0003
0·0002
0·0001
0
Vx = 0
0
1000
2000
3000
4000
STRESS N/m

Fig 5b

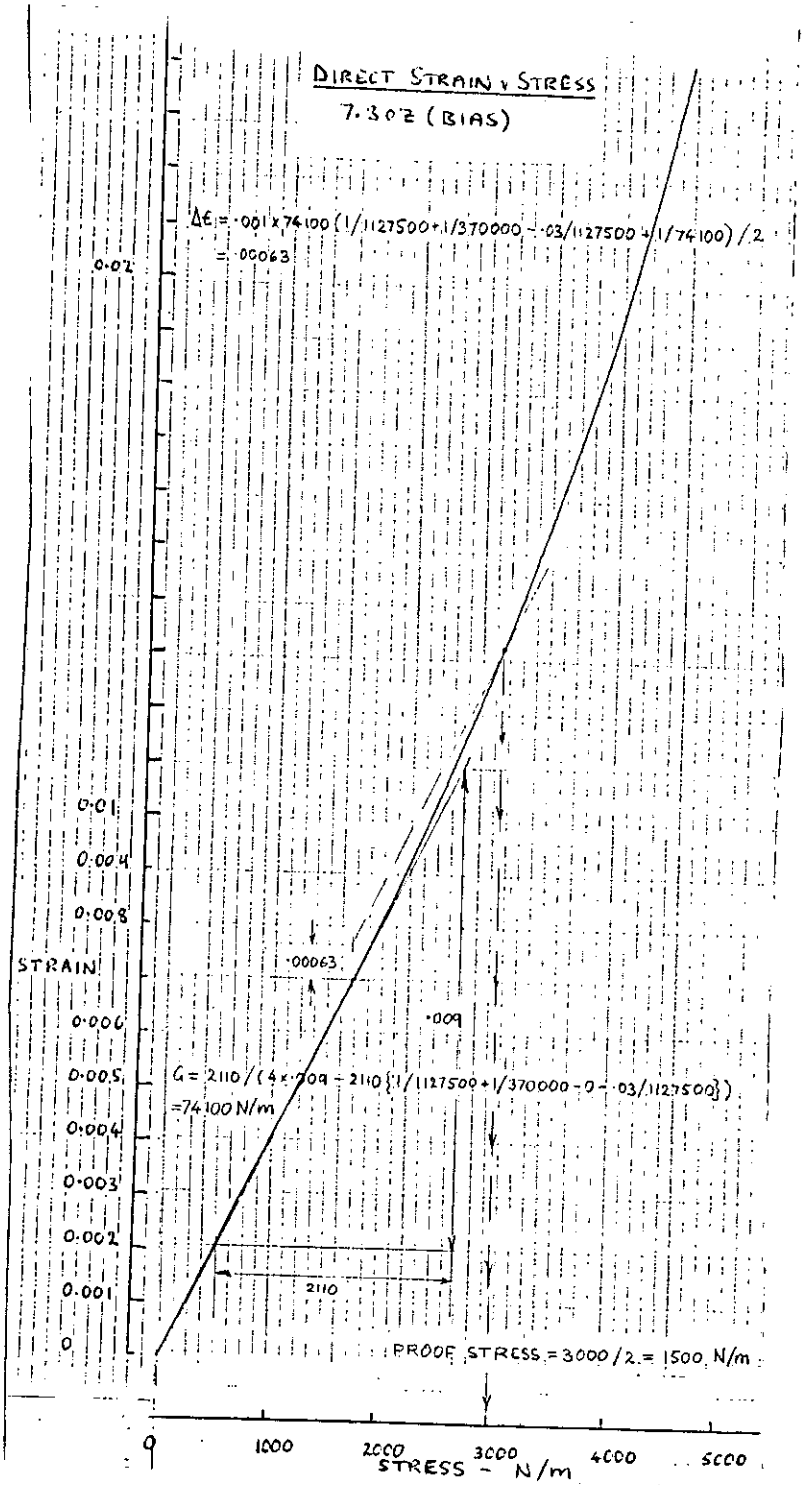

DIRECT STRAIN v STRESS
7.3oz (BIAS)
Δε = ·001 x 74100 (1/1127500 + 1/370000 - ·03/1127500 + 1/74100) /2
= ·00063
0·02
0·01
0·00.4
0·00.8
STRAIN
0·006
0·00.5
0·004
0·003
0·002
0·001
0
·00063
·009
G = 2110/(4x·009 - 2110{1/1127500 + 1/370000 - 0 - ·03/1127500})
=74100 N/m
2110
PROOF STRESS = 3000/2 = 1500 N/m
0
1000
2000
3000
4000
5000
STRESS - N/m

Fig.5c

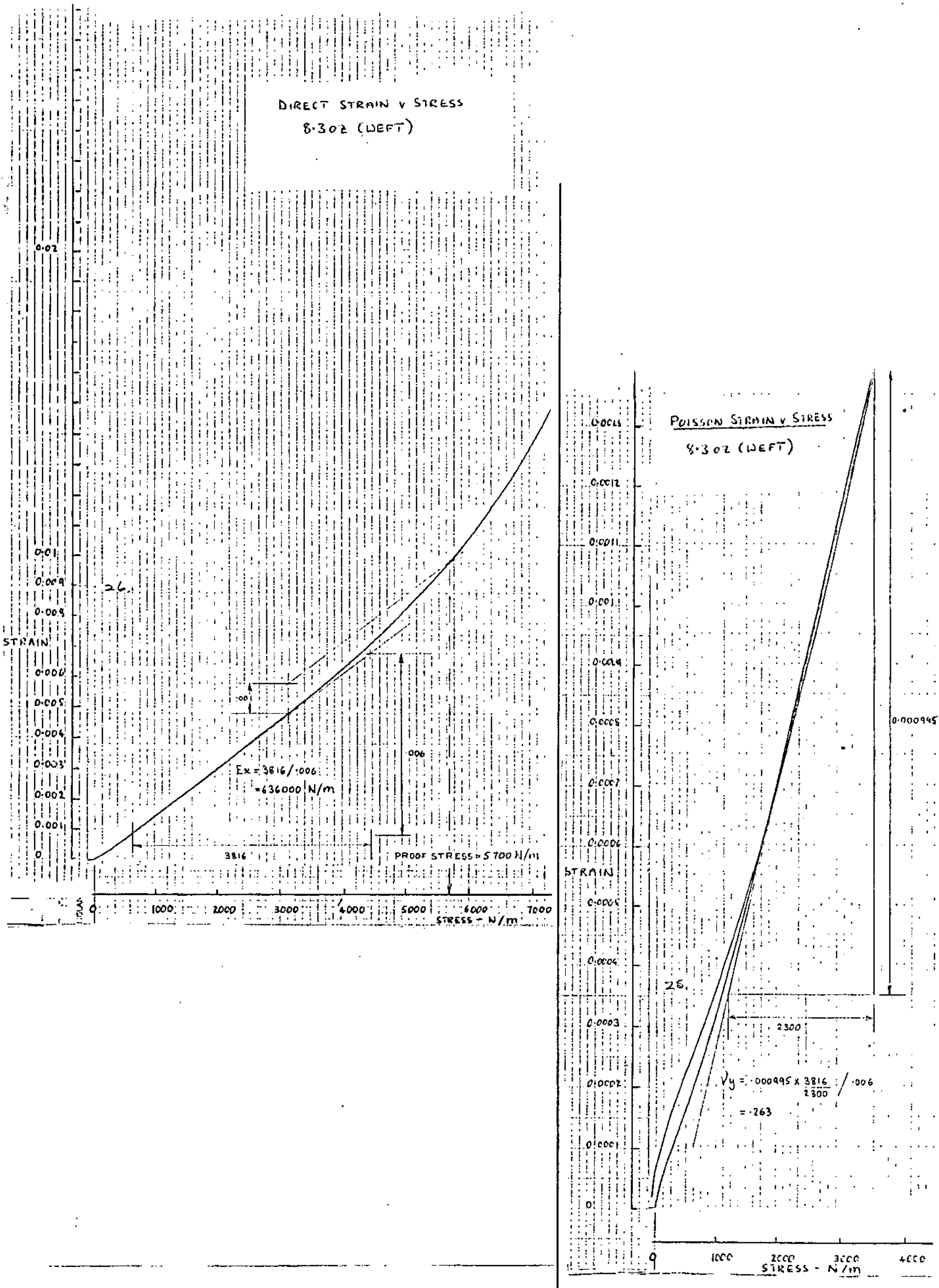

DIRECT STRAIN v STRESS
8·3oz (WEFT)
STRAIN
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
26.
·001
·006
Ex = 3816/·006
=636000 N/m
3816
PROOF STRESS = 5700 N/m
0
1000
2000
3000
4000
5000
6000
7000
STRESS – N/m
POISSON STRAIN v STRESS
8·3oz (WEFT)
STRAIN
0·0013
0·0012
0·0011
0·001
0·0009
0·0008
0·0007
0·0006
0·0005
0·0004
0·0003
0·0002
0·0001
0
0·000995
25.
2300
νy = ·000995 x 3816/2300 / ·006
= ·263
0
1000
2000
3000
4000
STRESS – N/m

Fig 6a

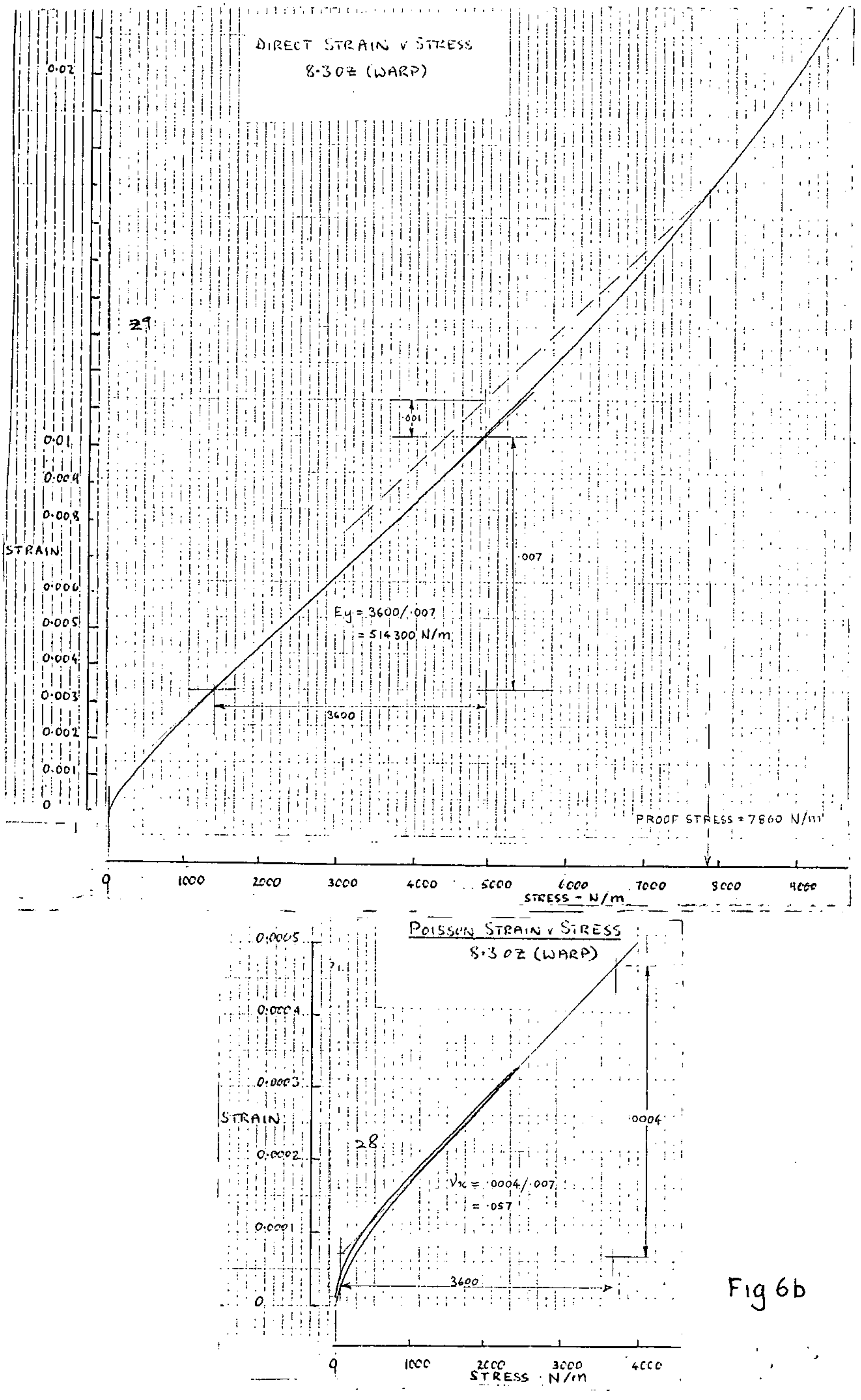

DIRECT STRAIN v STRESS
8·3 OZ (WARP)
0·02
29
0·01
0·009
0·008
STRAIN
0·006
0·005
0·004
0·003
0·002
0·001
0
·001
·007
Ey = 3600/·007
= 514300 N/m
3600
PROOF STRESS = 7860 N/m
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
STRESS – N/m
POISSON STRAIN v STRESS
8·3 OZ (WARP)
0·0005
0·0004
0·0003
STRAIN
0·0002
28
0·0001
0
·0004
νx = ·0004/·007
= ·057
3600
0
1000
2000
3000
4000
STRESS N/m

Fig 6b

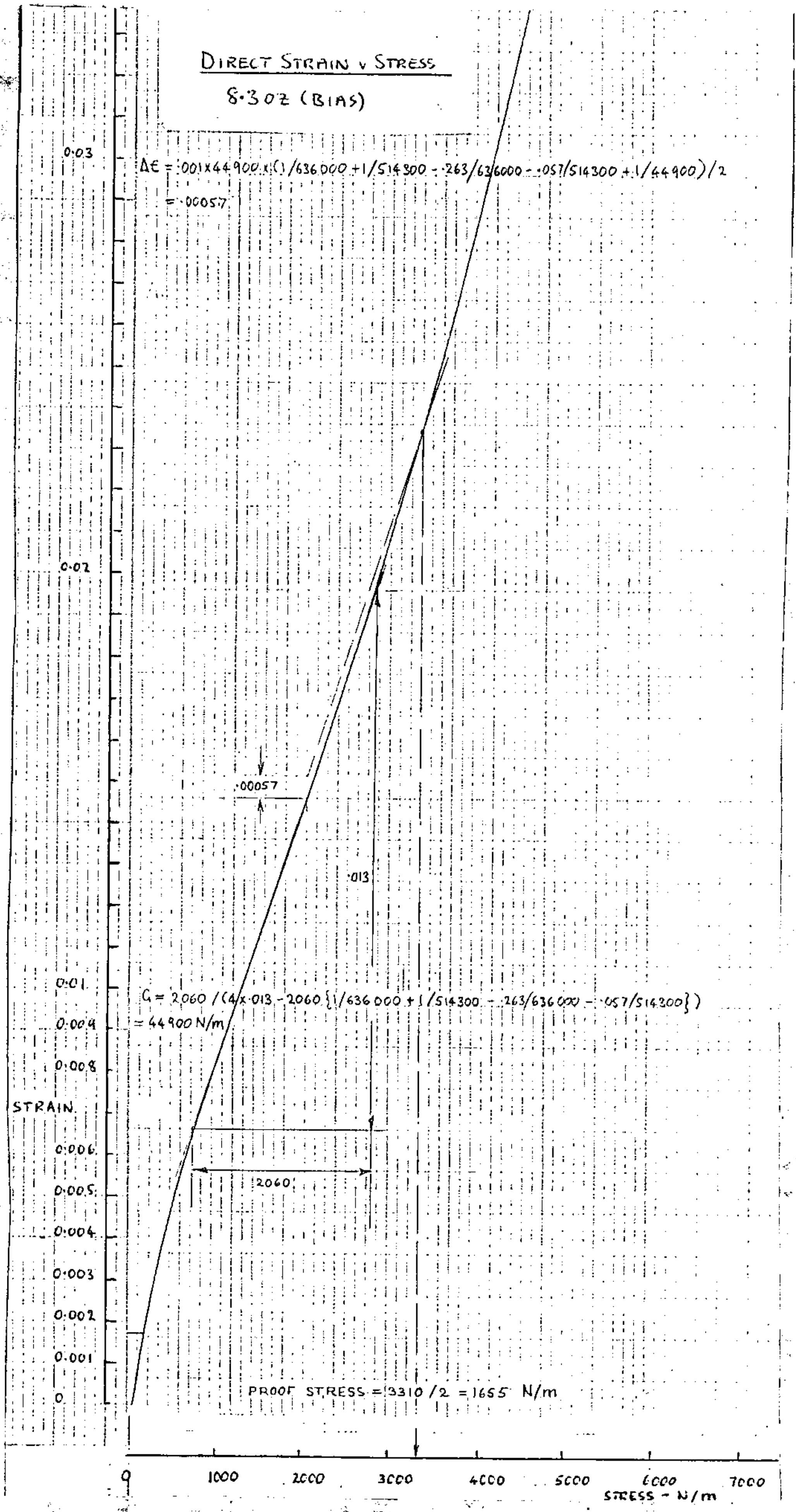

DIRECT STRAIN v STRESS
8·3oz (BIAS)
ΔE = ·001×44900×(1/636000 + 1/514300 − ·263/636000 − ·057/514300 + 1/44900)/2
= ·00057
·00057
·013
G = 2060 / (4×·013 − 2060{1/636000 + 1/514300 − ·263/636000 − ·057/514300})
= 44900 N/m
2060
PROOF STRESS = 3310 / 2 = 1655 N/m
STRAIN
0·03
0·02
0·01
0·009
0·008
0·006
0·005
0·004
0·003
0·002
0·001
0
0
1000
2000
3000
4000
5000
6000
7000
STRESS − N/m

Fig 6c

Table I

Results from Worked Examples

Cloth:	5.4oz	6.3oz	7.3oz	8.3oz	Unit
Ex:	510,200	986,300	1,127,500	636,000	N/m
Proof weft stress	4,400	7,250	9,300	5,700	N/m
νy	.18	.093	.03	.263	-
Ey	317,500	323,800	370,000	514,300	N/m
Proof warp stress	4,460	4,320	4,370	7,860	-
νx	0	0	0	.057	
G	22,800	40,700	74,100	44,900	N/m
Proof shear stress	730	1,370	1,500	1,655	N/m

Conclusions

The methods described enable the principal structural constants of sailcloth to be determined with the use of standard tensile test equipment. Choice of working stress levels must rest with the sailmaker, based on his assessments of stresses, vulnerability to mechanical damage and anticipated fatigue life. Such assessment might involve a fixed fraction of the proof stress for a given part of the sail. For example, the head region might be designed to carry 80% of the proof stress.

Over a period of time, it should be possible for a sailmaker to build up a background of experience from which to make realistic assessments of these fractions and ensure that no one part of a sail carries an excessive load. In the longer term, this should lead either to a longer sail fatigue life or a lighter sail.

These benefits might also be obtained by designing a sail so that principal stresses tend to be carried along warp and weft yarns. The table of results clearly shows that warp and weft proof stresses are about three times greater than proof shear stresses, indicating that shear stresses are best avoided.

Future work might examine the questions raised by stress interactions, mechanical damage, weathering and fatigue.

References

1. Satchwell, C.J. Elements of Lifting Membrane Analysis
S.U. PhD Thesis 1983 p6-30.
2. Timoshenko, S.P. and Gere, J.M. - Mechanics of Materials
Van Nostrand Reinhold p.64-79.
3. Timoshenko, S.P. and Goodier, J.N. - Theory of Elasticity
McGraw Hill Kogakusha Ltd. p35-40.