DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AEROSPACE ENGINEERING

Report LR-251

NON HOOKEAN BEHAVIOUR IN THE FIBRE DIRECTION OF CARBONFIBRE COMPOSITES AND THE INFLUENCE OF FIBRE WAVINESS ON THE TENSILE PROPERTIES

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SUMMARY

In the literature the tensile behaviour in the fibre direction of unidirectional carbon fibre reinforced plastic (c.f.r.p.) is assumed to be linearly elastic up to failure.
Some authors distinguish a primary and a secondary part in the stress-strain curve each showing Hookean behaviour.
The experimental results of this paper show that Young's modulus of laminates increases proportionally with the tensile stress, as found in Ref. [1] for single non-impregnated fibres.
An empirical relation between Young's modulus and the tensile stress is derived and the influence of fibre misalignment on this relation is examined.
In addition, the influence of fibre misalignment on the tensile strength and Poisson's ratio is discussed.

INTRODUCTION

During the past three years the composites departments of Fokker-VFW, the National Aerospace Laboratory - NLR and the Delft University of Technology have participated in a cooperative program for the testing and evolution of carbon fibre reinforced unidirectional epoxy laminates. In one phase of this program remarkable scatter was found in the results of tensile tests. Reasons for this scatter were assumed to be:

1. Non linear elastic behaviour of UD laminates due to non linearity in the stress-strain relation of a single, non impregnated carbon fibre, Ref. [1].
2. Fibre misalignments due to improper fabrication.
3. Errors in the determination of the fibre volume fraction caused by neglecting voids when using the Archimedes method. As an example Fig. 1 shows these errors.

Because of the importance of determining accurately the mechanical properties of c.f.r.p. laminates, additional tests were conducted to establish the relative importance of each of the three possible sources of error.

Since it is difficult to produce laminates with a homogeneous distribution of a well known void percentage, a number of laminates was produced with a void percentage as low as possible.

However a varied fibre misalignment was provided in order to measure stress-strain curves and the influence of fibre waviness on tensile properties.

The laminates which were produced consisted of six layers , each having an identical fibre waviness characterized by wavelength and amplitude. The layers were stacked arbitrary in order to obtain a more or less homogeneous distribution of misalignments over the laminate thickness. Non destructive inspection was performed with an ultrasonic scan method to investigate the laminate quality. Ref. [2]. From each panel ten tensile specimens were cut in the fibre direction. The dimensions and fibre contents are specified in Table I.

EXPERIMENTAL PROCEDURE

Young's modulus and Poisson's ratio were detemined by tensile tests which were carried out to approximately 60% of the ultimate tensile stress. Strains, parallel and perpendicular to the load direction, were measured with an extensometer and the reproducibility of the stress-strain curve was verified by multiple tests.

Since composites may behave visco-elastically the stress rate was varied from 400 to 3200 N/mm^2 per minute. Some of the tested specimens were prepared for ultrasonic determination of Young's modulus while the remaining specimens were loaded to failure with both constant stress rate and constant strain rate.

To determine the relation between Young's modulus and stress, the stress-strain curve was divided into segments each of which represented a load increase of 2000 N. For each segment the tangent modulus was calculated.

DISCUSSION OF RESULTS

All tensile tests show a non linear stress-strain relation, not affected by repeating the test and being independent of the stress rate within the considered range as shown in Fig. 2.
This is contrary to results normally found in literature. Ref. [3, 4].
In contrast to the non-linear relation just mentioned, the relation between Young's modulus and stress was found to be linear as shown in Fig. 3.
Table II contains the numerical results obtained from the measurements of Young's modulus while Fig. 4 is a plot of the data giving the E-σ relation for all the laminates tested. From the data of table II the following empirical E-σ relation can be derived:

$$E = E_o + 21\ \sigma \tag{1}$$

where E_o is Young's modulus at zero load. However since the ultrasonic measurement of Young's modulus is made at zero load, E_o corresponds directly to the ultrasonically determined Young's modulus.
The data of table III has been arranged to show differences between ultrasonic and mechanical measurements when the empirical formula is applied to this data. An increase of Young's modulus of about 30% between zero load and failure ($\sim$ 2000 N/mm^2) is observed.
The law of mixtures describing the relation between Young's modulus and fibre volumefraction is presented in Fig. 5.
It can be seen that a much lower scatter in the data appears when the E-values are related to stress level as described by the empirical formula.

As theoretically proved in Ref. [5], no significant influence of fibre misalignment on Young's modulus is found. The experiments verify this fact. There is a slight influence on the ultimate tensile strength as Fig. 6 shows. In contrast to slight influence of fibre misalignment on tensile strength, the influence on Poisson's ratio is ramarkable as shown in Fig. 7. Numerical results of the measurements of strength and

Poisson's ratio versus fibre misalignments are listed in table IV. Finally it should be pointed out that the test mode (load or stroke control) does not give different test results.

CONCLUSIONS

From the results of tensile tests on c.f.r.p. the following conclusions can be drawn.

- There occurs an increase in Young's modulus of about 30% between zero load and ultimate tensile strength.
- There is no influence of fibre misalignments on Young's modulus for the waviness considered.
- A modest negative influence on the ultimate tensile strength does occur for the misalignment considered.
- An increase of Poisson's ratio occurs with increasing waviness.
- Better application of the law of mixture results if the stress levels are considered.

Although the difference in Young's moduli for the unloaded and loaded condition tends to decrease to an acceptable percentage when a limited load range and safety factor are introduced, the effect of this phenomenon should not be underestimated.

Unlike metals, where stresspeaks are smoothed by plastic deformation, heavily loaded areas in carbonfibre reinforced materials will behave stiffer, attracting more load.

This tendency to increase stress concentrations might explain unexpected experimental results under conditions where notable stress variations appear in small areas, as may happen at stiffeners, around pin-loaded holes or in general in non-homogeneous stress fields.

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[4] Goggin, P.R. — The elastic constants of carbon-fibre composites. Journal of materials science, 8 (1973) 233-244.

[5] Knibbs, R.H., Morris, J.B. — The effects of fibre orientation on the physical properties of composites. Composites (Sept. 1974) 209-216.

Table I. Mean values of the dimensions and fibre volume constants of the ten specimens cut from each laminate

Laminate nr.	Thickness	Width	Length between tabs	Fibre content	Wavelength	Amplitude	Remarks
	mm	mm	mm	vol %	mm	mm	
73	1.28	14	100	61.3	55	0.75	
74	1.44	14	100	61.1	55	0.50	
75	1.38	14	100	63.2	55	0.25	
76	1.38	14	100	64.8	-	0	voids detected by C-scan
77	1.35	14	80	61.3	-	0	high void content detected by C-scan
79	1.30	14	100	67.8	55	0.20	
80	1.35	14	100	66.1	55	0.15	
81	1.41	14	100	67.0	55	0.10	
82	1.08	14	100	67.6	55	0.05	

Table II. Numerical results of the ultrasonical and mechanical measurement of Young's modulus

$$E = E_o + a\sigma$$

Laminate nr.	E_o N/mm^2	a	E_u N/mm^2
73	124,720	21.94	125,360
74	127,020	21.09	128,990
75	131,130	21.76	132,730
76	139,640	21.27	136,550
77	129,740	19.15	123,330
79	146,740	22.39	146,100
80	140,740	21.35	138,810
81	143,600	20.16	142,900
82	146,450	18.95	145,240

Table III. Comparison of mecanical and ultrasonic measurements of Young's modulus at zero load

Laminate nr.	$\frac{E_o - E_u}{E_o} \times 100\%$	Remarks
73	0.5	
74	1.5	
75	1.2	
76	2.2	voids detected by C-scan
77	5.0	high void content detected by C-scan
79	0.4	
80	0.7	
81	0.5	
82	0.8	

Table IV: Numerical results of the measurement of strength and Poisson's ratio versus fibre misalignment

Laminate nr.	Ultimate tensile strength N/mm^2	Poisson's ratio
73	1,440	0.52
74	1,540	0.36
75	1,870	0.27
76	1,820	0.32
77	1,790	0.30
79	1,850	0.30
80	1,880	0.28
81	2,010	0.29
82	2,000	0.29

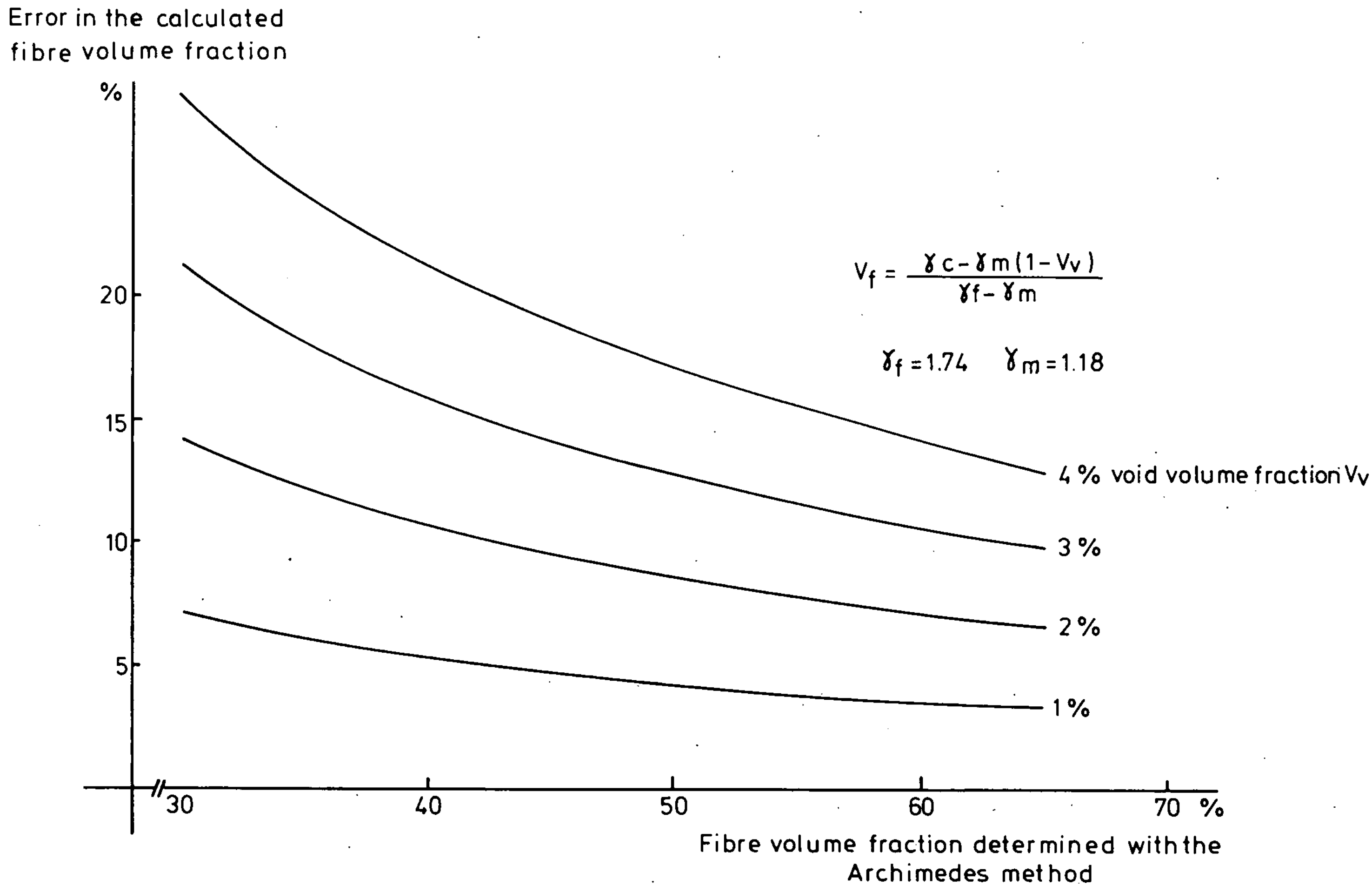

Figure 1 : Error in the calculated fibre volume fraction due to neglecting voids.

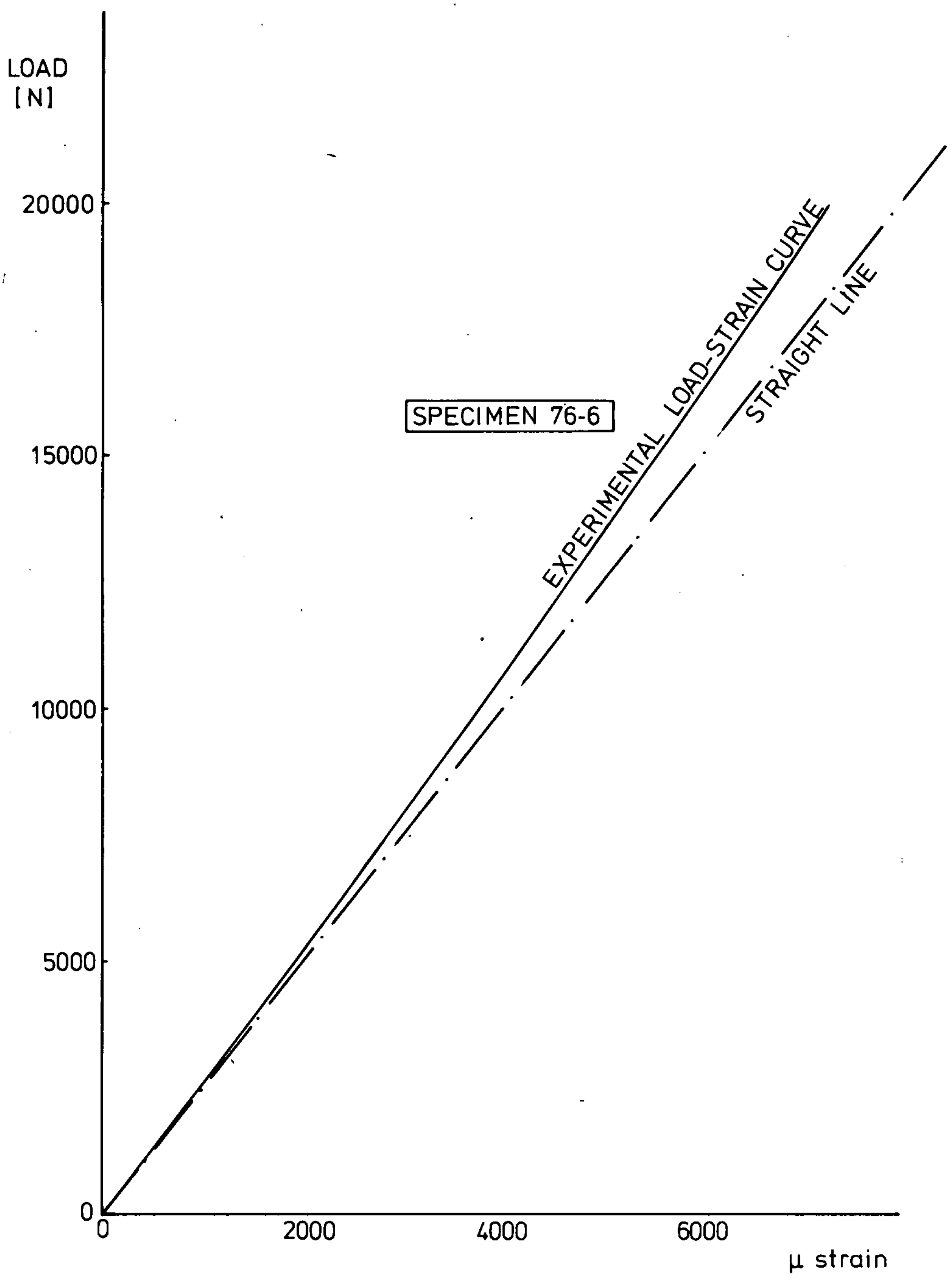

FIG. 2 : The load-strain curve of a UD cfrp laminate loaded in fibre direction.

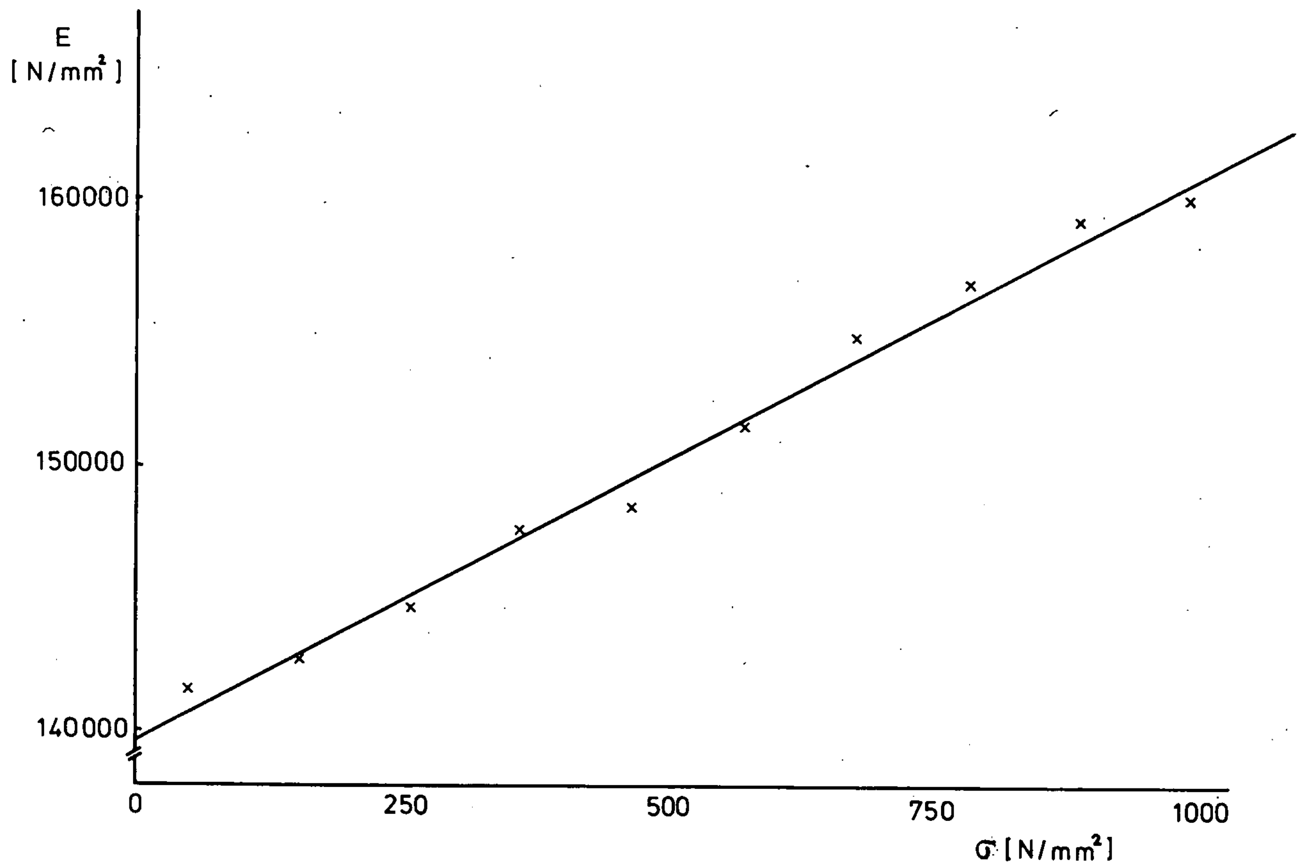

Figure 3 : The relation between Young's modulus and stress.
Data points on mean values for panel 76.

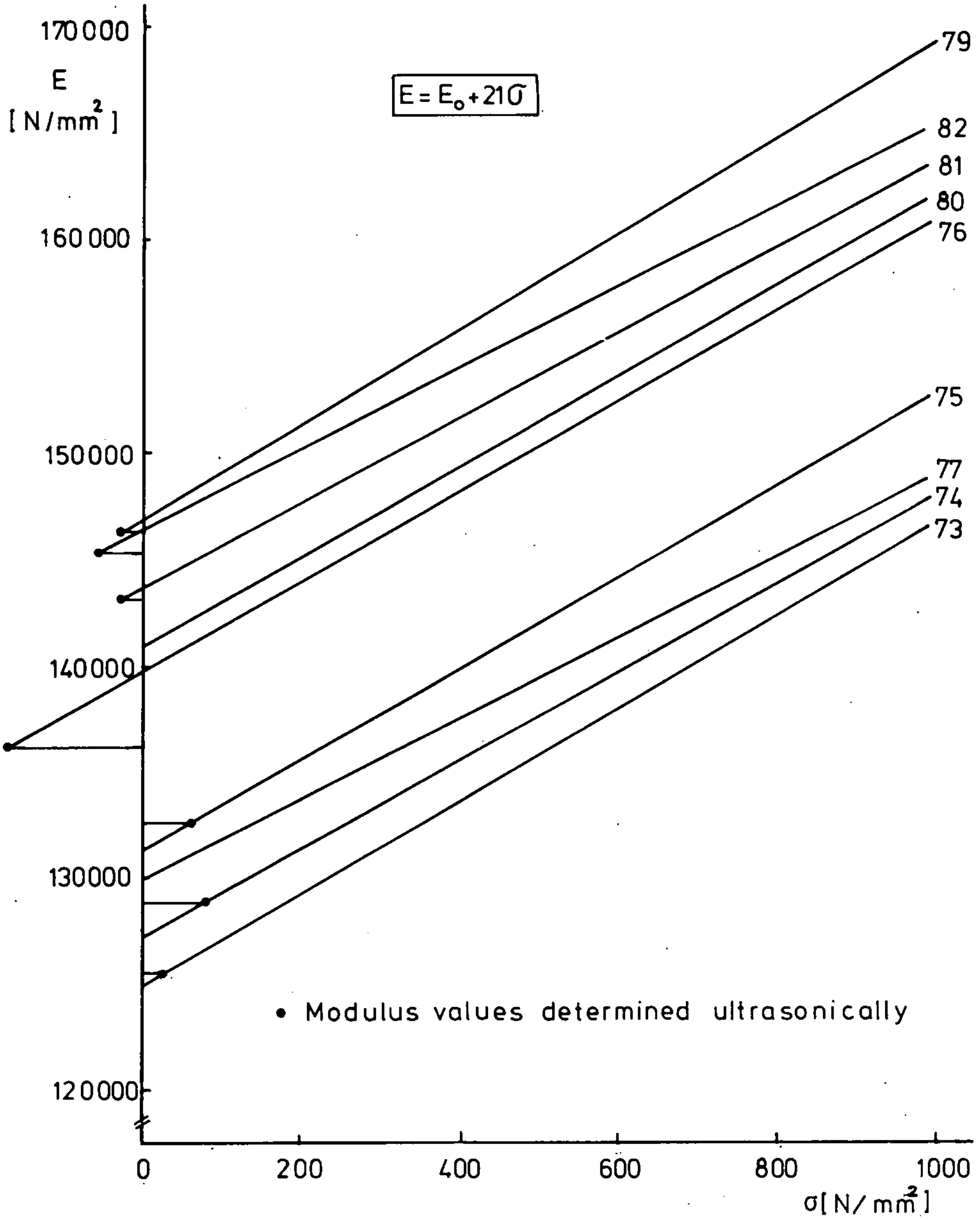

Figure 4: The relation between Young's modulus and stress determined from mean values for each panel.

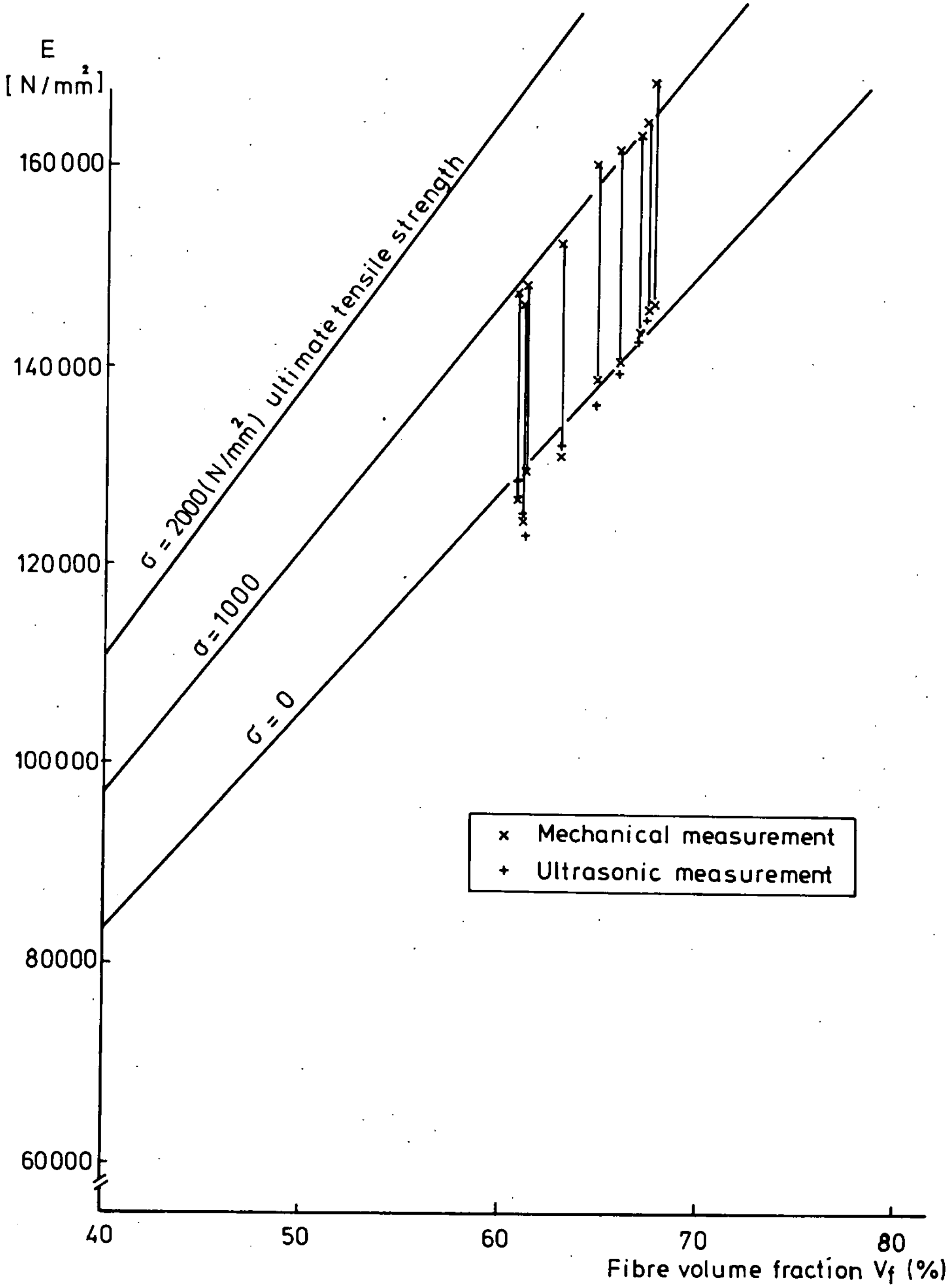

Figure 5: The law of mixtures refered to stress levels.

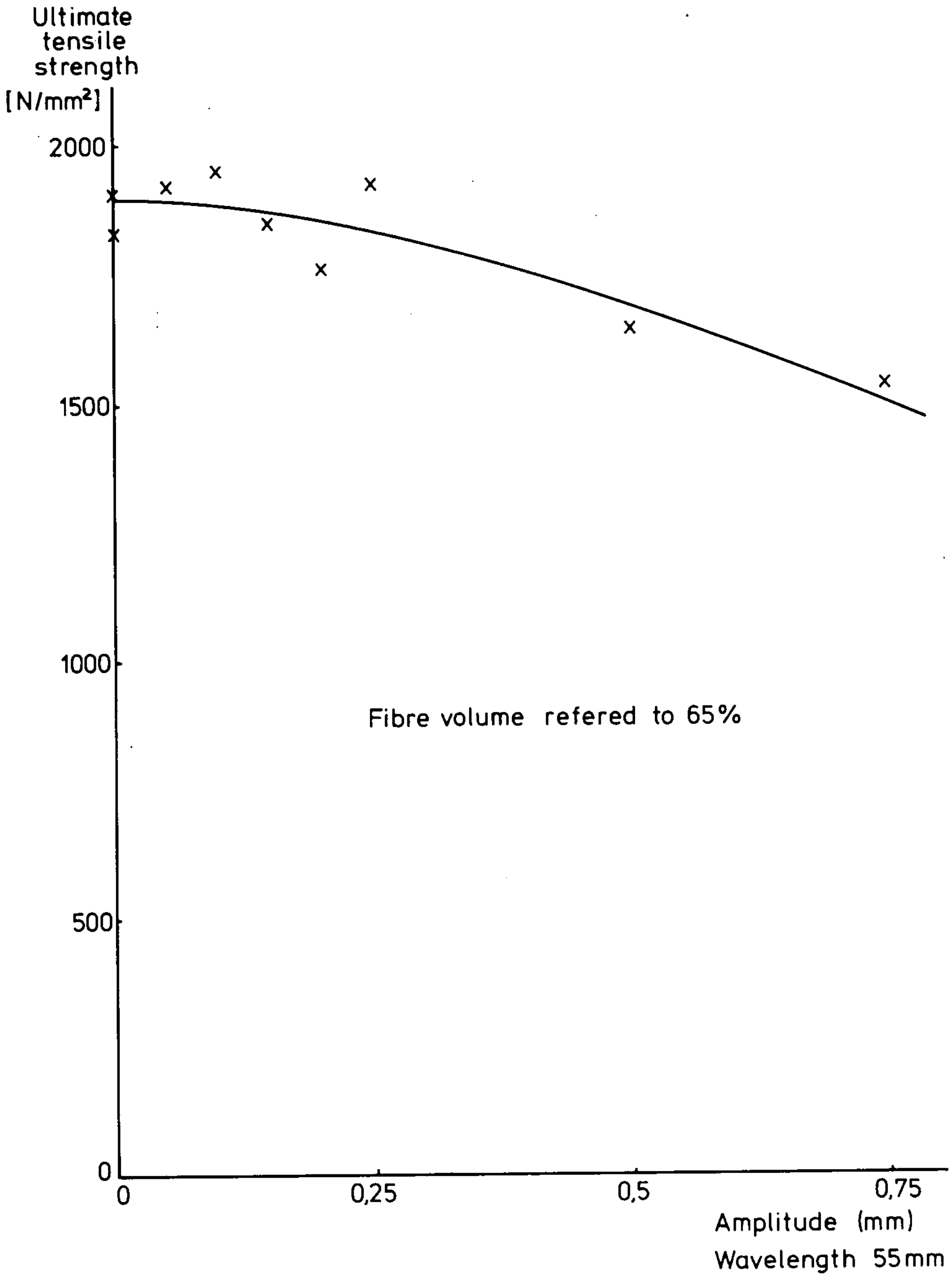

FIG.6: Influence of fibre waviness on ultimate tensile strenght

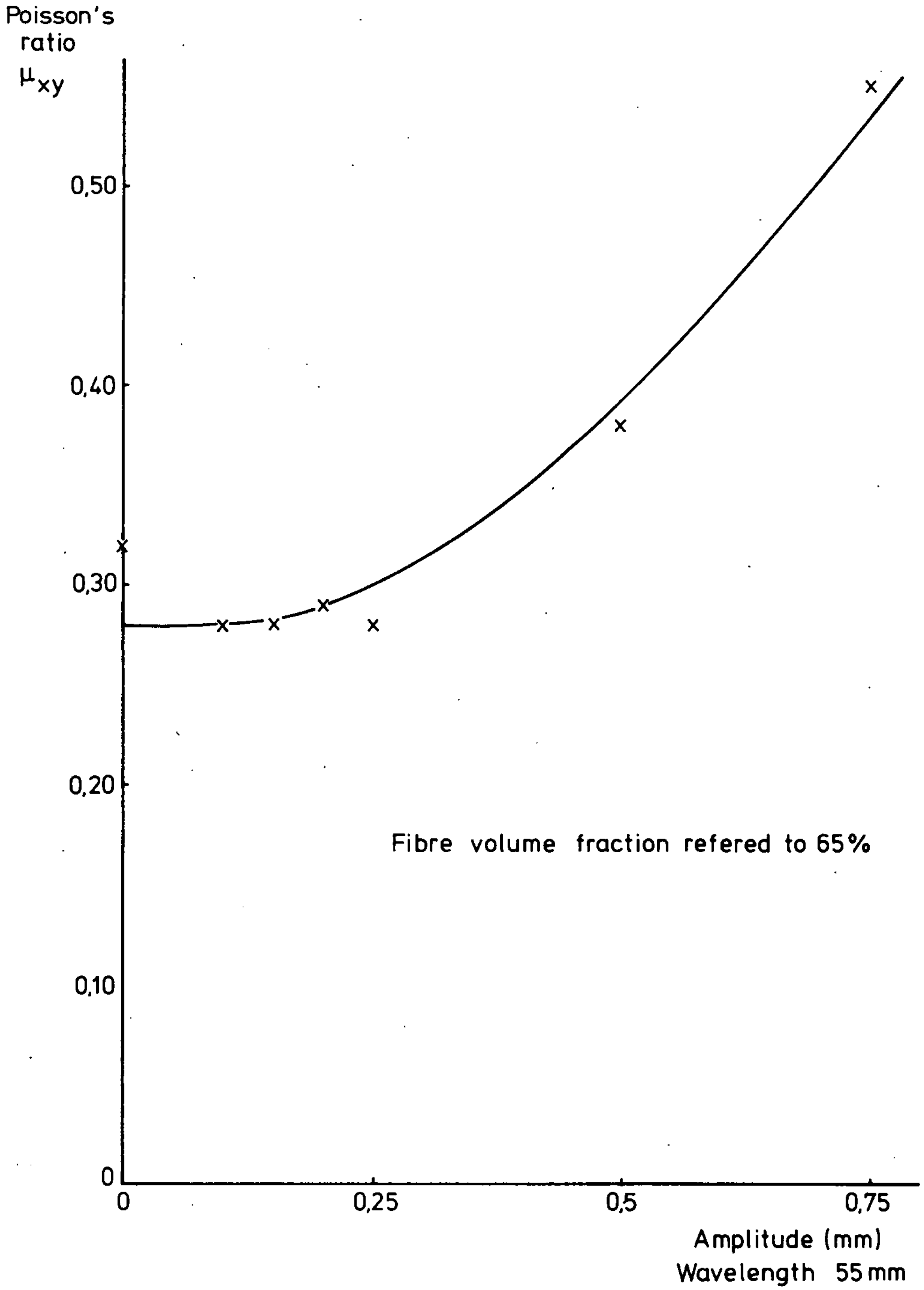

FIG. 7: Influence of fibre waviness on Poisson's ratio.

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