TRANSVERSE PROPERTIES OF BULK ARAMID FIBRES

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ABSTRACT: The determination of the transverse properties of a bundle of aramid fibres is described, for the purposes of using them in an analysis of the barrel and spike termination used for parallel-lay ropes. Tests on pads of fibre to measure the transverse elastic modulus are described, and the differences between the initial loading response, and the response to subsequent unloading and reloading are highlighted. The plastic behaviour as the pad is compressed is also discussed.

KEYWORDS: aramid fibre, Kevlar fibre, transverse properties, plasticity, elasticity.

1 INTRODUCTION

As part of a programme of work aimed at understanding and modeling the termination system for parallel-lay aramid ropes, a model of the bulk properties of aramid fibres was required. The termination, developed by Linear Composites Ltd. (Figure 1), grips the fibres between a specially shaped spike and a barrel with a conical hole. An annular pad of fibres exists between the barrel and the spike, and is subjected to a complex set of stresses, including the axial forces from the rope, and transverse stresses between the spike and barrel. There must also be shear stresses set up at the fibre/metal interface.

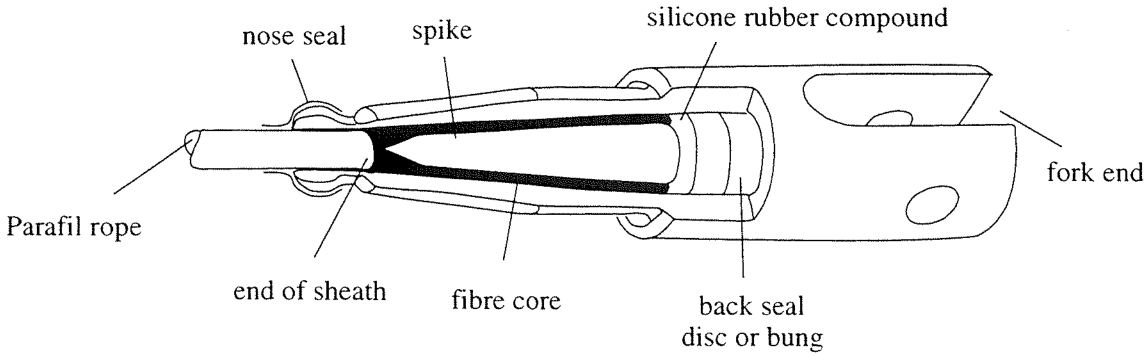

Figure 1. Parafil termination

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Various models can been be used to determine the behaviour of the termination, but the most sophisticated model requires a finite element analysis that can follow the material non-linearity in the fibre properties, and also the stick-slip friction that occurs on the surfaces. This paper relates to the determination of the properties of the fibre that are used within that finite element model. Both physical testing and theoretical analyses were carried out on aramid fibres. The particular aramid used for these tests was Kevlar 49, but it is believed that the phenomena and methods described here, if not the particular values, are relevant to all types of aramid fibres, and many other highly oriented polymers.

Kevlar 49, like all oriented synthetic fibres, exhibits orthotropy; the moduli and compliances are different in the longitudinal and transverse directions. This is due to the inherent asymmetry of the organic molecules that make up the fibres and the drawing that takes place during fibre manufacture. The ratio between the axial and transverse elastic moduli has been quoted as high as 170 [2], but this value was obtained by tests on single filaments, and the properties of the bulk fibre will be different. Many of the bulk properties will be affected by changes in packing density, as well as deformations of the fibres themselves.

Values of the axial Young's Modulus have been determined for bulk yarns and parallel-lay ropes, as well as single yarns. Because there is very little twist of the fibres in each yarn, and no twist of the yarns in the rope, the differences between the axial moduli are small (129.6 kN/mm^2 for the fibre [3], 126.5 kN/mm^2 for the rope [4]. However, there is no published data for the elastic and plastic properties of the bulk fibres in the transverse direction.

The rope has many voids between the individual fibres, and so initially does not behave like a solid; the fibre elastic compliances are thus irrelevant. Fortunately, aramid fibres deform plasticly under transverse loading whilst maintaining most of their axial strength [2], so the rope will continue to be squashed until there are no voids left, at which point it will behave like a solid. The bulk compliances will then be equal to those of a single fibre. It has been observed that the fibres in a Parafil spike-and-barrel termination are compressed together so tightly that no water can penetrate along the fibres, and the position of the spike after bed-down is consistent with all the voids being squeezed out of the rope. The fibres themselves probably take up various polygonal shapes with correspondingly large transverse plastic strains.

Synthetic fibres are viscoelastic [5,6], so the 'elastic moduli' should be regarded as time-dependent. For the purposes of this study, however, measurements were taken a fixed time after the application of load, so that the fibres can be regarded as anisotropic elastic solids. The experiments showed that, although there was some viscoelasticity, it was insignificant over the time scale of the tests.

2 PROPERTIES REQUIRED

It is reasonable to assume that aramids are transversely isotropic, but with different properties in the axial direction. Five parameters are then required to define the compliance matrix; these are, together with values obtained by Kawabata [3] on single filaments:-

E_L	The longitudinal modulus of the fibre (129.6 kN/mm^2).
E_T	The transverse modulus of the fibre - on single filaments, this is measured by compressing the fibre and measuring the change in the diameter (2.49 kN/mm^2).
G_{LT}	The longitudinal shear modulus, found by relating its shear stress to shear strain in a torsion test (2.01 kN/mm^2).
ν_{LT}	The longitudinal-transverse Poisson's ratio, found from filament tests (0.62).
ν_{TT}	The transverse-transverse Poisson's ratio, which is determined by making a composite plate with a high volume fraction of fibres, and pulling it in different directions (0.31).

The compliance matrix can then be expressed as

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{E_T} & \dfrac{-\nu_{TT}}{E_T} & \dfrac{-\nu_{LT}}{E_T} & 0 & 0 & 0 \\ \dfrac{-\nu_{TT}}{E_T} & \dfrac{1}{E_T} & \dfrac{-\nu_{LT}}{E_T} & 0 & 0 & 0 \\ \dfrac{-\nu_{LT}}{E_T} & \dfrac{-\nu_{LT}}{E_T} & \dfrac{1}{E_L} & 0 & 0 & 0 \\ 0 & 0 & 0 & \dfrac{1}{G_{LT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \dfrac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \dfrac{2(1+\nu_{TT})}{E_T} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \qquad (1)$$

in which x- and y- lie perpendicular to the fibre axis, while z- lies along it.

It was believed that for determining the behaviour of the termination, all the values given by Kawabata could be used, with the important exception of the transverse modulus, since this would be significantly affected by bulk inter-fibre effects. The value of ν_{TT} would also be significant, but since this was obtained from a high volume fraction composite, the value given above is already a bulk value rather than a single filament value.

3 MEASUREMENT OF BULK TRANSVERSE MODULUS

Blocks of fibre, obtained by removing sections from a suitably sized parallel-lay rope (which thus minimized handling of individual yarns) were placed inside a chamber which constrained them laterally in one transverse direction, but left them free axially (Figure 2). A force was then applied across the other transverse direction, and the force and corresponding displacement measured. The blocks were originally about 15 mm high (in the loading direction), and of various lengths and widths. The orientation of every individual filament could not be guaranteed, but the overall arrangement was deemed to be a suitable representation of a real fibre bundle.

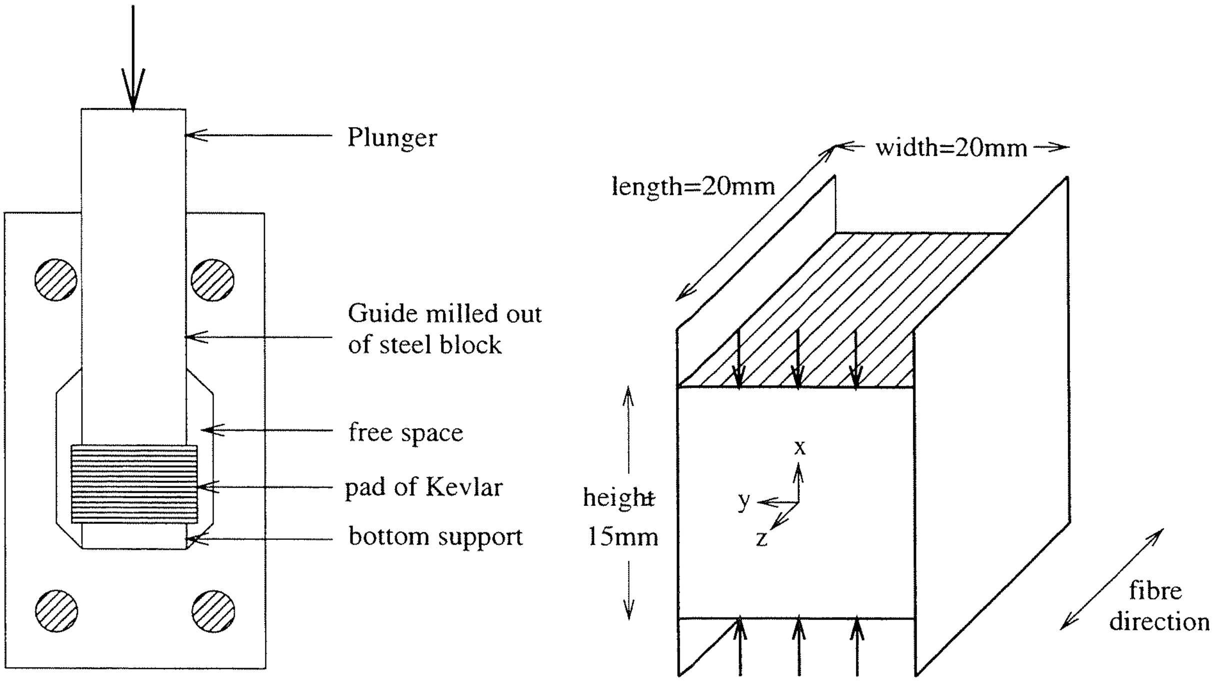


Figure 2. Compression test rig and fibre layout

The constraining chamber was made from steel blocks that could be bolted together after the fibres had been inserted, and the load was applied via a plunger. The assembly was designed to fit into a standard compression testing machine.

A typical load displacement curve is shown in Figure 3. It clearly shows that the fibre pad stiffens as the load increases, and also that the unloading/reloading response is very different from the first loading behaviour. This is significant when dealing with the termination analysis, since the initial bedding-in of the spike into the barrel will be governed by the initial loading curve, while subsequent loadings will depend on the unloading/reloading behaviour.

Figure 4 shows the modulus on loading as a function of applied load, for several different tests with different sizes of fibre pad. The values are consistent, and they are in the same range as the values quoted on single filaments. The finite element program, however, uses logarithmic strain (f(λ) = ln(λ)), rather than nominal strain (f(λ) = λ - 1), where λ is the ratio of current to original length. The values from the figure thus have to be suitably converted.

The unloading/reloading response (against log. strain) is shown in Figure 5 (with the length at 10 N/mm^2 taken as the base length to eliminate initial slack). There is clearly an increase in the stiffness of the unload/reload portions of the curve, as load increases.

For convenience in the finite element programme, which is heavily iterative in places, the modulus is averaged over stress bands, to avoid having to slow the program down while moduli are recomputed. The values quoted in Table 1 were thus used in the finite element analysis.

These values should be compared with the values quoted earlier for single filaments (2.49 kN/mm^2 for transverse modulus, and 129.6 kN/mm^2 for axial modulus).

Table 1. Transverse modulus E_T of bulk Kevlar 49 fibres.

Stress Range (N/mm^2)	Initial Loading Modulus (kN/mm^2)	Unloading/Reloading Modulus (kN/mm^2)
0 - 27	0.27	1.8
27 - 72	0.45	5.8
72 - 136	0.85	16.4
>136	1.90	(not determined)

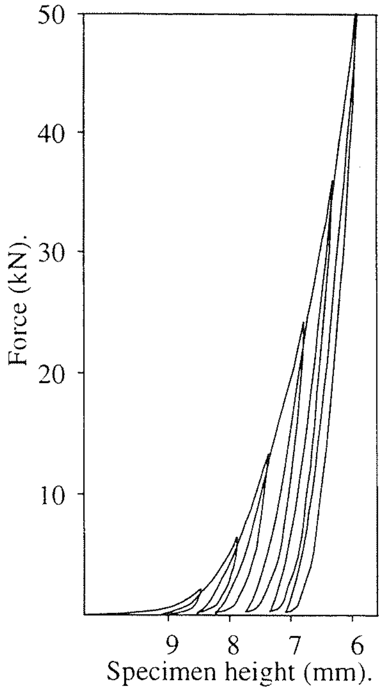


Figure 3. Typical load-deflection response

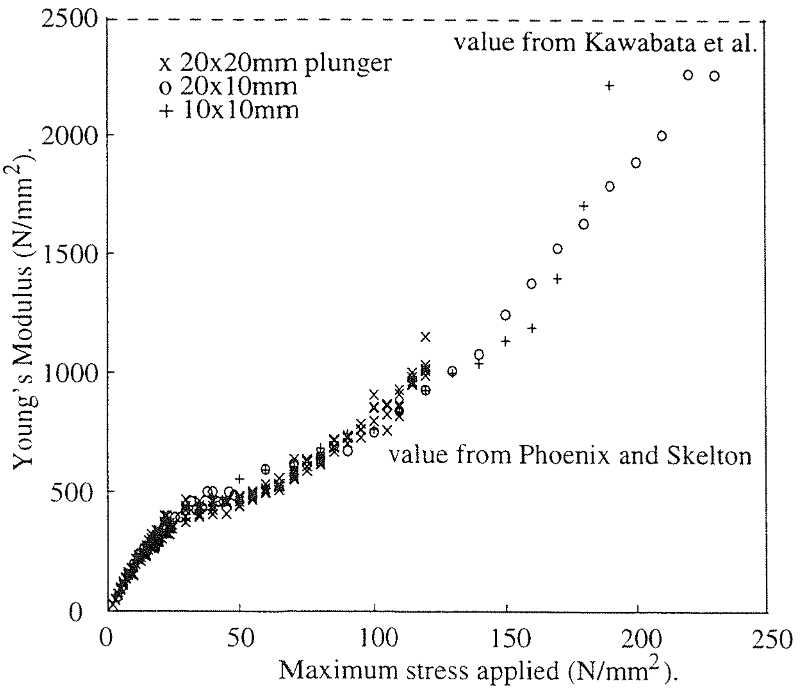


Figure 4. Modulus on loading vs. maximum stress

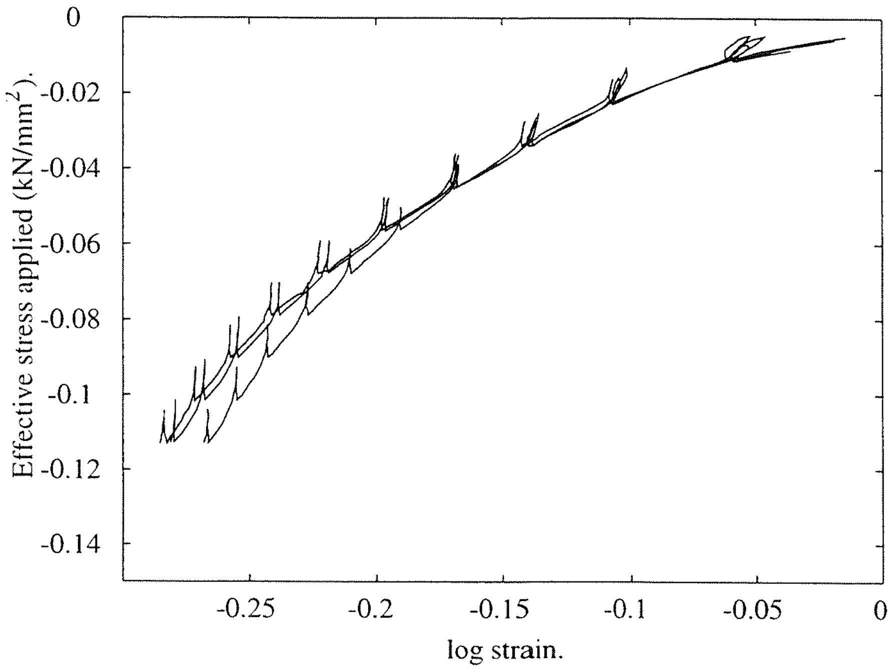


Figure 5. Transverse stress-log strain
for unloading/reloading

4 PLASTICITY OF FIBRES

One aspect of interest was the question of whether the fibres could be assumed to deform plasticly when loaded transversely. A variety of analyses were carried out and compared with the test results (Figure 6). In this figure, the horizontal scale is the ratio of the specimen height to the height with no voids (1.27 corresponds to perfect rectangular packing, 1.10 corresponds to perfect hexagonal packing). It is deemed to be unlikely that a figure of 1 could be obtained, even at very high pressures. Curves 1, 2, 3 and 4 give the results of four different compaction tests. There is some variation, but the overall pattern is consistent.

Various theoretical analyses were also carried out. The relevant material properties used were a transverse Young's Modulus 2.49 kN/mm^2, Poisson's ratio 0.31 and a uniaxial yield stress of 320 N/mm^2, which was taken as twice the value of 160 N/mm^2 quoted for the shear yield strength [2]. A finite element analysis was carried out on a quarter of the cross section of one fibre, squashing it in one direction until it flattened (Figure 7). The results of this analysis are shown as curve x on Figure 6. These results are broadly in agreement with the test results. Curve y shows the results of a simple plastic slip-line analysis deforming a single fibre towards a hexagon - this clearly does not match the test results. Finally, for comparison purposes, the predictions of an elastic deformation analysis assuming the single filament transverse modulus, is shown as curve z. It is only the slope of this curve which is of interest, rather than its horizontal position, and it is clear that when fully packed, the fibre pad response matches this stiffness quite well.

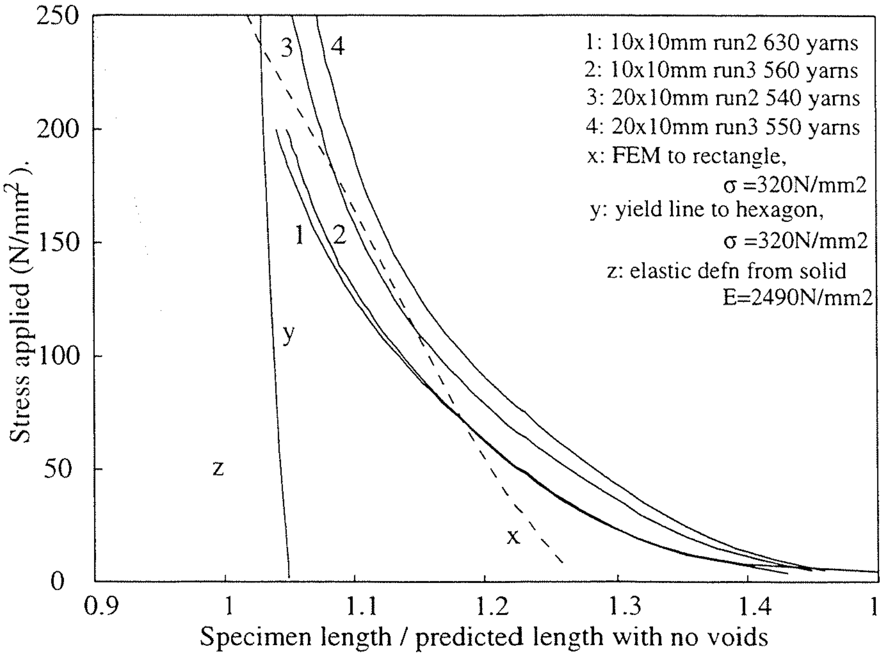
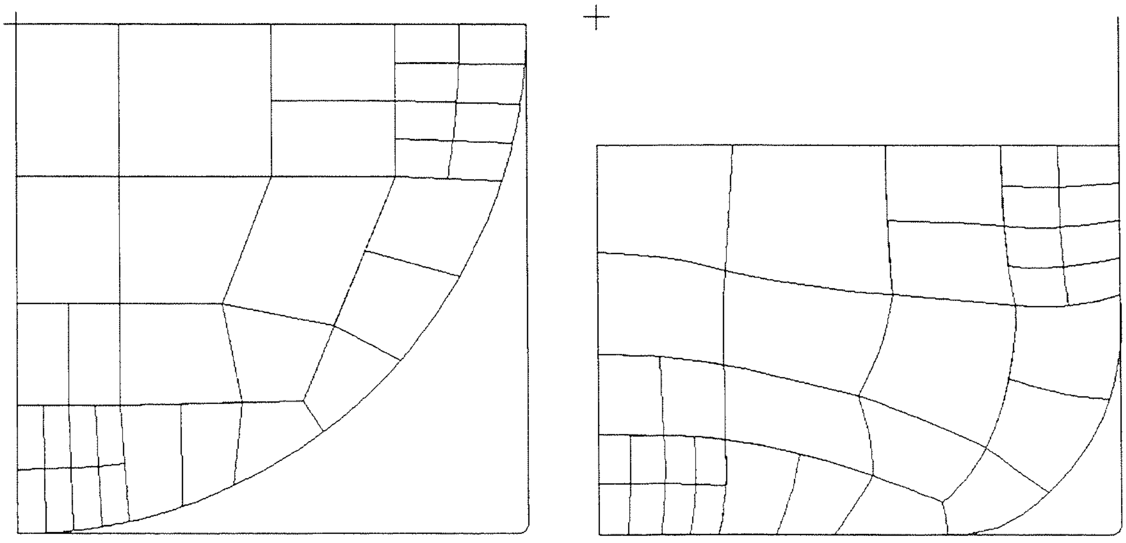


Figure 6. Compression of Kevlar 49 pad towards fully packed condition



Undeformed

Deformed

Figure 7. Finite element modeling of gross deformation of fibre

5 CONCLUSIONS

It has been shown that the response of a pad of fibres to transverse load is significantly different from the response of a single fibre. Tests have been carried out to determine the transverse elastic modulus of the pad, which is shown to differ between first loading and subsequent unloading and reloading. Suitable values have been calculated for use in a finite element analysis of a termination.

It has also been shown that the behaviour, as packing densities increase, is consistent with the assumption that the fibres deform plasticly, with a uniaxial tensile strength of 320 N/mm^2.

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