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Visco-elasticity of aramid fibres

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Abstract Tests are described to measure the creep and relaxation response of aramid fibres with the specific aim of determining whether the visco-elastic response is linear or non-linear. Hitherto, creep and relaxation tests have been carried out in different circumstances and at different loads, which has led to disagreement about the type of response that aramid fibres exhibit. Tests are carried out at stresses between 10% and 80% of the short-term strength of the fibres under controlled temperature and humidity conditions, and it is shown that both creep and relaxation are non-linear at stresses below 40% of the breaking load, but both are linear at stresses above this level. This result explains the contradictions in earlier work and also indicates that there may be two different processes underway in the visco-elasticity of aramids.

Background

Aramid fibres are being considered for use in many structural engineering applications [1]. Many of these applications would require the fibres to be under long-term or permanent loads, and uncertainty about their visco-elastic properties is one of the principal reasons why industry is unwilling to commit to their use. The uncertainty is reflected in several ways, and the present work is part of a larger study [2] to remove that uncertainty. The main concern is with the stress-rupture behaviour, in which the fibres creep to failure, and with the uncertainty caused by the need to extrapolate to structural lifetimes (typically 100 years) from tests that are carried out over a short time-scale (frequently hours, but even in the best circumstances, less than a year).

Detractors can also point out that the literature is not even consistent on whether the fibres are linearly or non-linearly visco-elastic. There have been several studies that have not resolved the matter, which are complicated by the fact that there are different versions of aramid fibres which are available in different forms.

Aramid fibres are available in various grades and from several manufacturers. Kevlar (made by Du Pont) and Twaron (originally made by Akzo, now part of Teijin) are very similar chemically although they may differ slightly in their physical structure. The various grades are believed to differ only in a heat treatment imposed during manufacture. It is reasonable to suppose that a similar visco-elastic mechanism will apply to the different grades, although the creep rates can be expected to differ. Technora, another aramid fibre manufactured by Teijin, and Vectran, manufactured by Kuraray, differ chemically so they may behave differently. All the results presented in this paper were obtained from a single batch of Kevlar 49 yarns.

Guimaraes and Burgoyne [3] tested parallel-lay ropes made from Kevlar 49 yarns and concluded that aramid fibres possess a linear visco-elastic behaviour. However, Walton and Majumdar [4], who tested Kevlar 49 fibre and fibre-cement composites, showed that the visco-elastic behaviour of aramid fibres is non-linear. From stress-relaxation tests, Ko [5], who tested Kevlar 49 yarns and, Amaniampong [6] and Chambers [7], both of whom tested parallel-lay ropes of Kevlar 49 yarns, claimed that the

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visco-elastic behaviour is non-linear, but Schaefgen [8] showed that aramids exhibit linear behaviour. Amaniampong's study [9] was largely concerned with bundle theory; he concluded that creep-rupture results (and by extension, creep itself) on bundles and individual fibres could be compared if the loads were normalised by the short-term strength of bundles of different sizes.

The most comprehensive study has been carried out by Northolt. In early studies [10] he showed that the response to tensile load was made up of a linear elastic response plus an irreversible rotation of crystallites. He tested various grades of aramid fibres made by Akzo, with static moduli ranging from 55 GPa to 105 GPa. This work was extended and corrected [11] in a model that assumed that the fibrils were made up largely of zig-zag crystals whose orientation significantly affected the modulus. This work was however concerned only with the short-term response. Later, Northolt and Baltussen [12, 13] extended the model to deal with visco-elasticity. They concluded that there are two phenomena that contribute to the visco-elastic behaviour; one is a linear visco-elastic shear deformation, and an increased tendency of the fibrils to align with the loading direction, which relates to the analysis performed in the earlier model.

The work of Northolt and his collaborators was used as the basis for the work by Chailleux and Davies [14]. They modelled Twaron 1000 fibres as a non-linear visco-elastic material with both viscous and frictional damping components. It should be noted that most of their results were obtained at stresses below 1 GPa, which is at the lower end of the range of stresses considered here.

One of the problems with many of these studies is that the results were often obtained as by-products of other work. Most of the creep testing was carried out as part of studies of stress-rupture. In order to obtain failures in reasonable time, the stress levels were high, typically above 70% of the short-term strength of the fibres. In contrast, relaxation tests were carried to determine the losses of force that would be expected at the sort of loads to which fibres are permanently exposed. In many rope applications there is considerable uncertainty about the loads, so large nominal safety factors are used. Thus, these tests have often been performed at low loads, almost always below 50% of the break-load of the fibres. Thus, there is almost no data that has been obtained in similar circumstances for both creep and relaxation at comparable stress ranges.

The lack of overlap would not necessarily be a problem if it was certain that no change in material behaviour occurred at different stress levels. There is, however, evidence that aramid yarns stiffen at about 50% of their short-term strength (Fig. 1 [7]). Thus, most creep test data have been obtained at stress levels above this load, while the stress-relaxation test data have been obtained below this load.

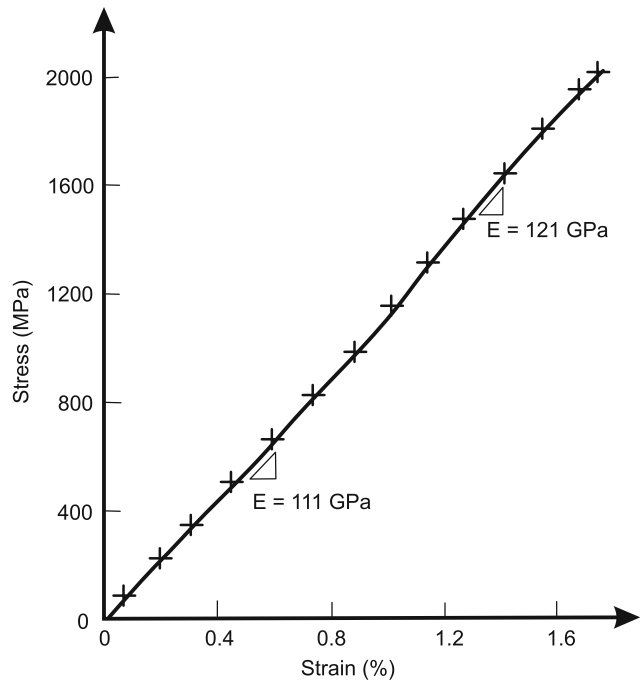

Fig. 1 Stress–strain response for Kevlar 49 yarns reported by Chambers [7]

The aim of the present study was thus to obtain both creep and relaxation data at a full range of loads. Fibres from the same batch would be clamped in the same jaws, in the same environmental conditions and at similar load levels. The results would then be comparable.

Linear and non-linear visco-elasticity

The behaviour of a visco-elastic material under general loading is complex, but two states are normally identified for laboratory testing: creep and stress-relaxation. Creep is the change in length of a specimen over time under a constant stress. Relaxation is the variation of stress under a constant strain. If creep strain is plotted against applied stress after a fixed time, and the results are linear and pass through zero, the material is said to behave in a linearly visco-elastic manner. Similarly, stress-relaxation is linear if a plot of stress-reduction against initial strain after a fixed time gives a straight line which passes through zero.

Visco-elasticity is best explained by state theory (see, for example [15]); this assumes that there exists a unique relationship between stress σ, creep strain ε_c and time t for a given material (Fig. 2):

$$\varepsilon_c = \phi(\sigma, t) \quad (1)$$

If the variables are separable, ϕ may be represented as the product of two functions:

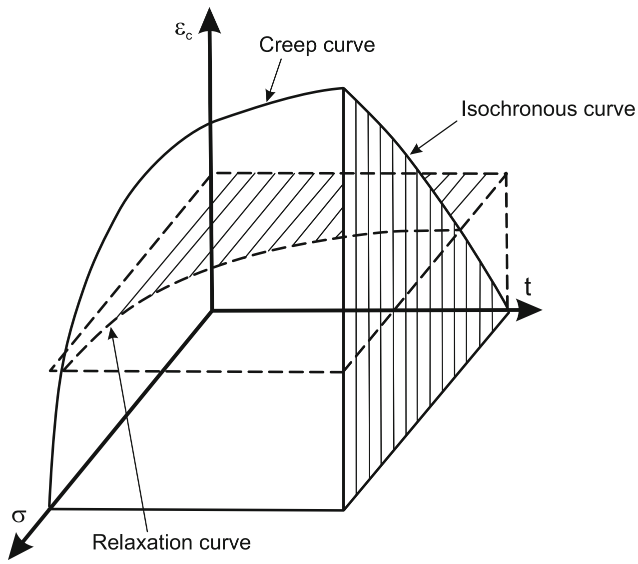

Fig. 2 Generic 3-D Stress–strain–time response

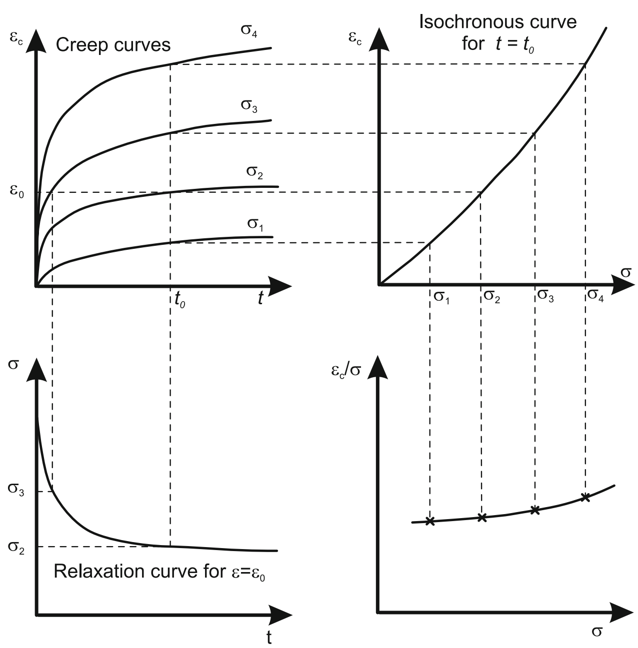

Fig. 3 Interdependence of 2D stress–strain–time curves

$$\varepsilon_c = \phi(t)f(\sigma) \quad (2)$$

If the material is linearly visco-elastic, $f(\sigma) = \sigma$, and Eq. 2 becomes:

$$\varepsilon_c = \phi_c(t)\,\sigma \quad (3)$$

where $\phi_c(t)$ is the creep compliance and σ is the stress.

Sections drawn through the surface of Fig. 2 at constant stress level produce creep curves, while sections taken at constant strain produce relaxation curves. An important cross-plot is the stress-strain curve at a specific time t_0, which is referred to as the isochronous curve and can be obtained from Eq. 3.

A linearly visco-elastic material has a linear isochronous curve which can be used as a simple check on this property, but such a plot is difficult to produce without a very full set of data. As an alternative, the ratio of $\phi_c\left(= {}^{\varepsilon_c}/_{\sigma}\right)$ vs. σ should give a straight line parallel to the σ axis if the material is linearly visco-elastic. The latter method is used in this analysis (Fig. 3).

Materials whose strain at any state is a function of both time and stress are defined as non-linear visco-elastic materials. Their isochronous curves are not straight.

Visco-elasticity using creep curves

To discuss visco-elastic behaviour, it is necessary to:

- Carry out tests to obtain creep curves at different stress levels,
- Analyse the results to obtain creep coefficient values corresponding to different creep curves at a specified time, t_0,
- Plot $\phi_c(t_0)$ vs. σ to check whether the material is linearly visco-elastic.

Visco-elasticity using stress-relaxation curves

Isochronous curves for stress-relaxation can also be found in an analogous way. According to the state theory, a material is said to be linear if the following ratio is stress independent [15]:

$$\frac{\sigma_r(t)}{\sigma_0} = \lambda(t) \quad (4)$$

where σ_0 the initial stress; σ_r the stress relaxation; λ the stress relaxation coefficient.

Amaniampong [6] showed that the stress-relaxation data of aramid ropes with 1.5 and 3 tonne breaking loads could be modelled with a logarithmic time function:

$$\sigma_i(t) = \sigma_{0i} + \delta_i \log(t) \quad (5)$$

where $i = 1, 2, 3\ldots$,etc. for curves at different initial strain conditions; σ is the total stress.

Equation 5 can be rearranged to give the relaxation coefficient λ.

$$\lambda_i(t) = \frac{\sigma_i(t) - \sigma_{0i}}{\sigma_{0i}} = \frac{\delta_i}{\sigma_{0i}}\log(t) \quad (6)$$

If λ varies with initial stress the material is non-linearly visco-elastic, whereas if it is constant then the material is linearly visco-elastic.

Chambers [7] obtained a relationship for the 100 h stress loss as a function of the initial stress for aramid ropes with a 60 tonne nominal breaking load (NBL):

$$\sigma(100) = \sigma_{0i} + 1.82 + 4.03 \times 10^2 \sigma_{0i} \quad (7)$$

(where his stresses were expressed as percentages of the NBL).

This can be rearranged to give:

$$\lambda_i(100) = \frac{\sigma(100) - \sigma_{0i}}{\sigma_{0i}} = \frac{\sigma_{0i}}{1.82} + 4.03 \times 10^2 \quad (8)$$

The stress-relaxation coefficient is stress dependent, so aramids possess non-linear visco-elastic behaviour. This result was confirmed by Amaniampong [6]. Schaefgen [8], on the other hand, showed that aramid fibres possess linear visco-elastic behaviour. The tests described below were designed to resolve this apparent discrepancy.

Test procedures

Yarns tested

All the tests described here were carried out on 1000 filament Kevlar 49 yarns of 2426 decitex. The yarns were supplied with a nominal 80 turns/m twist which was believed to give the optimum strength for these fibres. Table 1 shows the properties of the Kevlar 49 yarns used in this experiment. Twelve yarn specimens were tested in an Instron testing machine and the average breaking load (ABL) found to be 445 N with a Standard Deviation of 8.22 N. All subsequent loads will be described as a percentage of this figure.

Environmental chamber

The tests were all carried out in an environmental room, originally built to keep concrete specimens in controlled conditions. The environmental equipment could raise and lower the humidity, but only raise the temperature. It was thus decided to keep the humidity at 65% RH while the temperature was held at 25 °C, slightly higher than the ambient room temperature. The room was well inside the main laboratory building, and had thick walls, so occasional higher temperatures outside did not cause temperature excursions in the room. The original intention had been to carry out a single set of tests lasting approximately 2 years, but problems with the environmental equipment and data-logging equipment meant that several series of tests had to be carried out. The results presented here are thus for a larger number of tests of shorter duration, and for those tests which were not affected by the equipment failures.

Table 1 Properties of Kevlar 49 yarns

Material property	Values
Cross-sectional area of a yarn	0.16853×10^{-6} m^2
Average breaking load	445 N[a]
Average length of a yarn specimen	400–500 mm
Average strain capacity (literature)	1.5–2%
Young's modulus (literature)	120 GPa

[a] Average of 12 tests

Creep experiment

The yarns were subjected to constant loads, applied by dead-weights. Strains were measured over a long period by specially made strain gauges connected to a data logger. Several rigs were mounted on stiff frames, which were bolted to the wall. The yarns were mounted vertically, with the top clamp fixed and the bottom one free to slide within guides, but loosely restrained against twist. The load was applied by concrete weights on a threaded rod, acting via a 5:1 lever arrangement. Minor adjustments were made to the load by adding small bags of sand and the total weight checked by measuring the weight before the test. To avoid shock loading on the yarn, the weight was initially supported on a small scissors-jack which could be lowered slowly by turning a handle. The load was applied over a period of a few seconds, but precise loading rates could not be controlled. Figure 4 shows an overall view of the experimental set-up.

Yarn clamps

Because a large number of long-term tests would be carried out, it was not feasible to use standard yarn-testing jaws. Instead, a clamping arrangement has been developed in which the test yarn passes $^7/_8$ turn around a bar of 20 mm diameter, and is then clamped between plates (Fig. 5). These clamps have been used for all the tension, creep, and relaxation tests reported here, and also for creep-rupture tests that are reported elsewhere [2, 16, 17]. The clamps were designed so that they can be moved from the creep rig to a tensile testing machine without disturbing the fibre, in order to allow strength-retention tests to be performed. Experience has shown that failure does not normally occur at the jaws. Any tests where failure did not occur in the free-length of the yarn were discarded.

An extensive set of tests has also been undertaken to determine the jaw effect, although they are not relevant here since the strain (in the creep tests) or force (in the relaxation tests) were measured directly.

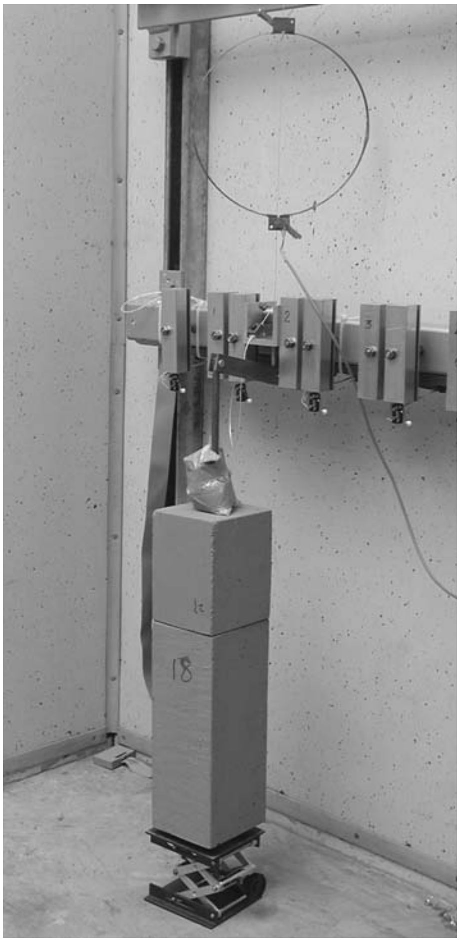

Fig. 4 Creep test rig showing sprung–steel strain gauge (top), lever arrangement (centre), and concrete dead weight (bottom), here supported on scissors jack before loading

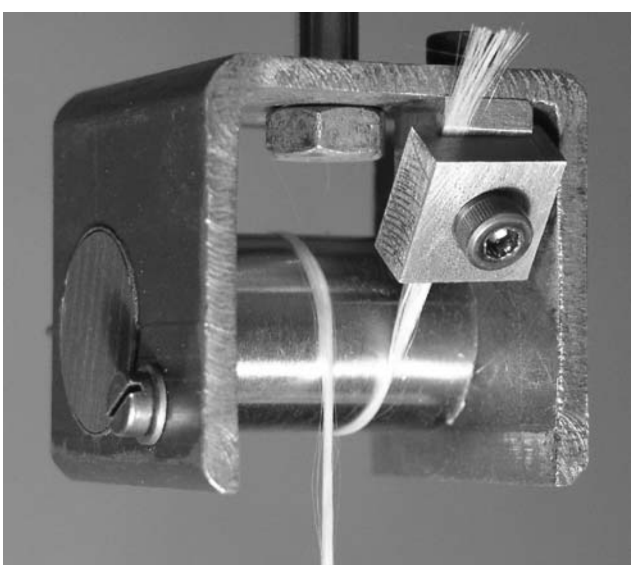

Fig. 5 Typical yarn clamp used for all tests

Procedures have been developed to minimise the handling of the yarns between unwinding from the bobbin and the start of the test. Such handling cannot be eliminated entirely and must remain a source of error, but the same procedures were used for all tests described here, so the results should be self-consistent.

Strain gauges

It was necessary to measure the strains in each yarn and to test many yarns at the same time to cover a range of load conditions. A simple mechanical strain gauge was used which could be mass produced. Each strain gauge was made with two strips of spring steel combined together to form a ring. Small holding clips were used to attach the gauge to the yarn specimen with small strips of rubber at the contact point to minimise stress concentrations. Experience has shown that these gauges are reliable and do not cause failure to take place at the clip positions in tension tests. Two pairs of electrical resistance strain gauges were attached to the steel; one on the inside and one on the outside of the ring at points remote from the clips. They were connected together to form a full bridge circuit that could be interrogated using a standard data logger. The construction method meant that each gauge differed slightly, so every gauge was calibrated using a jig. The self-weight of the gauge is around 1 N and the spring force at maximum extension is a fraction of a Newton. Thus, the additional load that would be applied to a yarn specimen could be neglected.

Data acquisition system for the creep test

A data logger was set up to measure the strain in each yarn, together with the temperature and the humidity in the environmental chamber. While the load was being applied the data were recorded every second; this was later extended to 2 min intervals, and after 1 day the interval was extended to 20 min. If a specimen began to creep more rapidly, indicating possible imminent failure, the data logging interval was automatically reduced to 1 s until failure occurred. The data were subsequently downloaded for analysis.

Test procedure

In the first set of tests, the load was applied after the strain gauge was fixed and initialised to zero. However, the yarn was observed to be slack when the gauge was being fixed. To overcome this initial slack, a small unknown load was applied by partially releasing the scissors jack before the strain gauge was fixed and initialised to zero. The initial strains were subsequently adjusted to enable the different test results to be compared.

A preliminary series of tests was performed on a tensile testing machine to obtain an accurate stress–strain curve for the yarns; a curve as precise as possible was needed for the Stepped Isothermal Testing which was carried out in association with this work. Tests were carried out on a variety of gauge lengths, at controlled extension rates of 5 mm/min, and were subsequently adjusted to allow for jaw effects and initial slack. The specimens had not been preloaded. A detailed description of this method is given elsewhere [17], from which Fig. 6 has been taken which shows the stress–strain response for instantaneous loading at 25 °C. It shows a stiffening of the fibres as the load increases, but not the sharp change in stiffness reported by Chambers [7], who tested fibres which were nominally the same as those tested here. These values were used to adjust the initial strain levels of the creep curves. It was assumed that the strain in the yarn, immediately after loading with the full, known, test force lay on this curve, which then allowed the true zero for the strain gauge readings to be determined. The process introduces a minor error since a small amount of creep takes place while the strain gauge is being attached, and also while the full load is being applied, but this will be very small and will be similar for each of the tests.

Eighteen yarn specimens were tested, in each of the three sets of tests, covering a wide range of stress levels. As with the creep tests, full details are given elsewhere [2]. Two specimens were tested under similar stress conditions and the results averaged and reported as one test. Yarns loaded at 80% ABL failed within a few hours of stressing and caused small shocks to be transmitted to the other yarns through the support frame. Tests at 75% and 80% ABL were not carried out in the later test series.

Stress-relaxation test

As with the creep tests it was necessary to carry out a number of stress-relaxation tests at the same time, which required the fabrication of a number of test rigs, each equipped with its own load cell. Figure 7 shows one of the test rigs; four steel rods provide the reaction frame, with the yarn specimen fixed to standard clamps as described above.

The top connection was fixed to a bolt that passed through a load cell. The bolt was placed in a self-centring washer that was located on the top face of the load cell. This ensured that the bolt would not touch the surrounding end plates as the load was applied by turning the nut on the top of the load cell.

Load cell

The load cell is the most important part of the test rig (Fig. 8). It is in the form of a standard double-ring proving

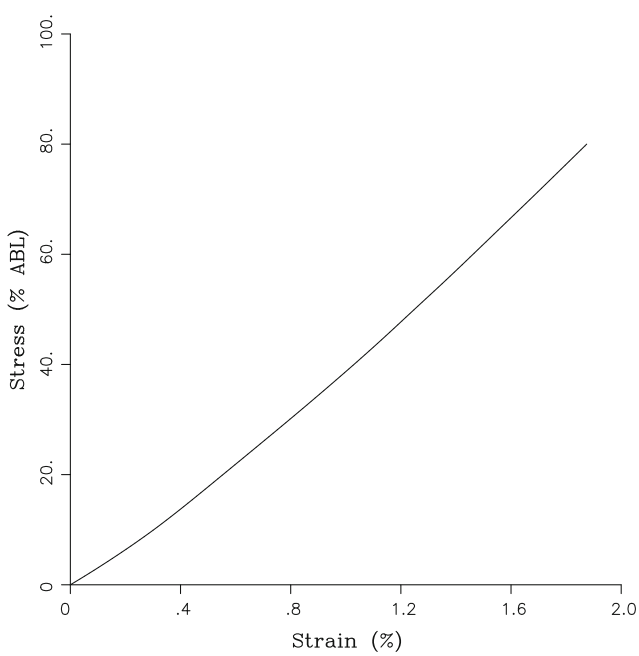

Fig. 6 Accurate stress–strain response measured in these tests

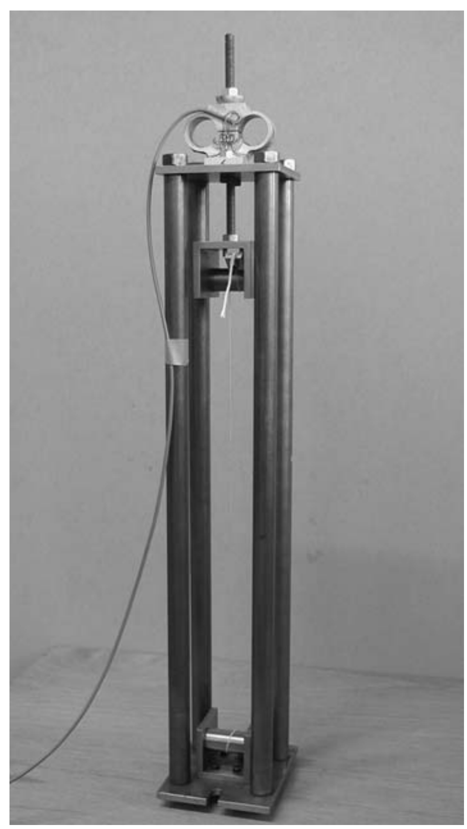

Fig. 7 Stress-relaxation test rig

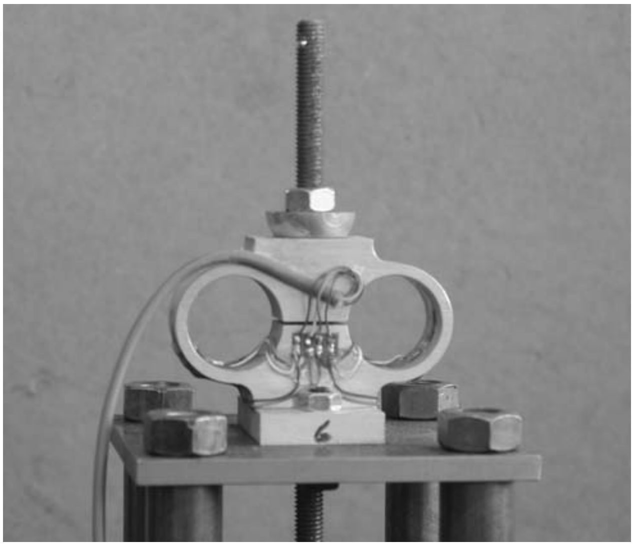

Fig. 8 Load cell used in stress-relaxation rig

cell, with a small gap between the upper and lower portions. The cell is made by spark erosion in a numerically controlled machine, so virtually identical cells can be produced with reasonable economy. Four strain gauges are fixed on the inside and outside of the circular parts of the load cell and a full-bridge circuit can be formed. Before starting the tests, all load cells were calibrated using the Instron testing machine and recalibrated afterwards to check that no drift had occurred. The load cells were connected to separate load measuring displays from which the data were recorded by hand.

Stressing operation

The yarn was stressed by tightening the nut against the top face of the load cell using a spanner. When the voltage reading had reached the desired value the stressing operation was stopped but it was very difficult to precisely achieve the desired load; the recorded initial stress was used in the analysis. As with the creep test it was very difficult to achieve a given loading rate; typically the load would be applied over a period of about 10 s. This was not felt to be significant given the long duration of the loading period, provided that shock loading was avoided.

Ten stress relaxation rigs were made and yarns were loaded with a wide range of stress levels. More attention as paid to carrying out tests at high load levels where existing data are limited. The relaxation tests were disturbed by the same failures of the environmental equipment, so four sets of tests of relatively short duration were carried out.

Results and discussion

Creep tests

Creep tests were carried out as described above. The results of the three tests are discussed separately.

1. *Creep test-1*: This test had to be discarded within 4 days due to failure of the air conditioner. Thus, data up to 75 h were considered valid.
2. *Creep test-2*: This test was carried out in a similar way to the creep test-1. However, very high load levels were not used to avoid premature stress-rupture failure. The test had to be abandoned after 1,080 h due to failure of the humidity control unit. Figure 9 shows typical strain versus log-time results from this set of tests, which is representative of those measured in all test series. The creep results are almost linear, but have a slight tendency to turn upwards at later times. Some of the more lightly loaded yarns crept more rapidly than some of the more highly loaded samples, despite great care being adopted to use the same procedure in each case.
3. *Creep test-3*: This test was similar to the creep test-2 and was carried out for 1,100 h.

Figure 10 shows the calculated creep compliance from all three series of tests at $t = 10$, 50, 100, and 800 h; Tables 2 and 3 shows the data in more detail. The compliance values have been calculated by dividing the creep strain (in %) by the stress normalised as a percentage of the Actual Breaking Stress (2640 N/mm^2).

Some of the more lightly loaded yarns in Test 2 crept more rapidly than some of the more highly loaded specimens and gave higher creep coefficients than the other two test series, in some cases significantly. There may well be

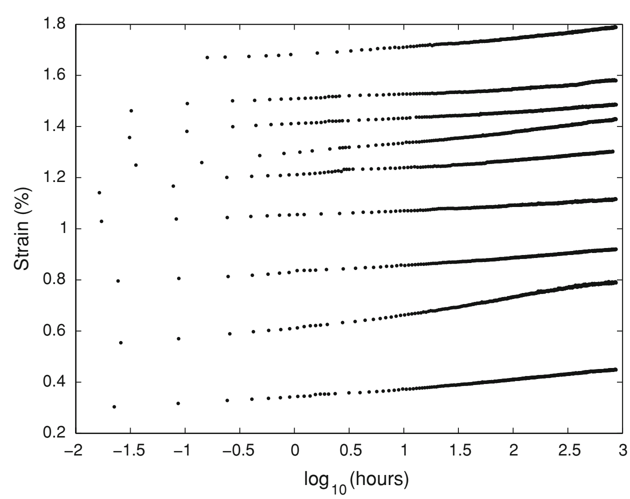

Fig. 9 Typical creep response from creep test 2

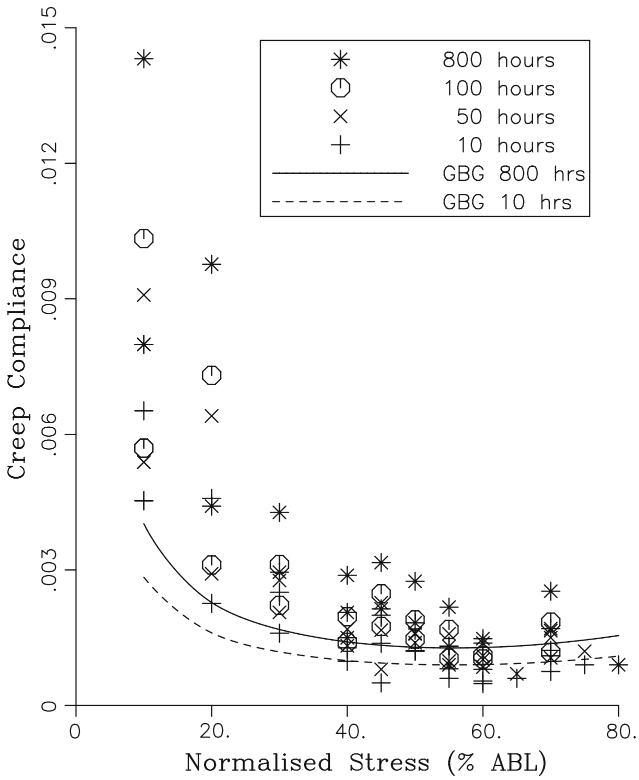

Fig. 10 Creep compliance against initial stress for all tests

some inherent material variability but the exact value of the compliance relies on the skill of the tester in fixing the yarns with the same degree of slack into the jaws, and also depends on the exact value chosen for the initial strain, which has to be done immediately after the loading when the creep is taking place most rapidly. These tests were carried out by the same person, using the same equipment, on yarns taken from the same reel, and the results processed in the same way.

Despite the variability, the figure clearly shows that there is a significant change in creep coefficient at a stress of about 40% ABL. Above this stress level there is very little change in the creep coefficient, which implies a linearly visco-elastic material, while below that level the response is non-linearly visco-elastic. It is also noticeable that there is much more variation at low stress levels than at high stress levels.

A similar analysis was carried out by Guimaraes [18] on Kevlar 49 yarns. His particular concern was to measure the creep on yarns and ropes, and to investigate the possibility that yarns which had been preloaded, even for a short time, suffered significantly less creep. Each specimen was tested at constant temperature (25 ± 2.5 °C) and humidity (75 ± 7%), for a period of 72 h, a time period sufficient to study primary creep and the beginning of secondary creep.

Table 2 Creep Compliance (Creep strain (%)/Stress (% ABL))

Load Level (%ABL)	Test No.	Test duration (hours)			
		10	50	100	800
10	2	0.00652	0.00909	0.01034	0.01432
	3	0.00453	0.00539	0.00570	0.00799
20	2	0.00459	0.00641	0.00731	0.00977
	3	0.00226	0.00292	0.00311	0.00441
30	2	0.00251	0.00277	0.00312	0.00427
	3	0.00160	0.00206	0.00222	0.00295
40	1	0.00150	0.00150	–	–
	2	0.00128	0.00169	0.00196	0.00288
	3	0.00098	0.00132	0.00140	0.00206
45	1	0.00050	0.00080	–	–
	2	0.00200	0.00227	0.00247	0.00316
	3	0.00138	0.00167	0.00175	0.00214
50	1	0.00120	0.00160	–	–
	2	0.00120	0.00158	0.00190	0.00275
	3	0.00121	0.00139	0.00147	0.00183
55	1	0.00060	0.00090	–	–
	2	0.00132	0.00159	0.00168	0.00218
	3	0.00081	0.00098	0.00104	0.00131
60	1	0.00080	0.00110	–	–
	2	0.00054	0.00085	0.00103	0.00148
	3	0.00048	0.00102	0.00111	0.00138
65	1	0.00060	0.00070	–	–
70	1	0.00110	0.00150	–	–
	2	0.00122	0.00166	0.00185	0.00253
	3	0.00075	0.00105	0.00117	0.00170
75	1	0.00090	0.00120	–	–
80	1	0.00090	0.00090	–	–

Five different stress levels were considered (10, 20, 30, 40, and 50% ABL). Six specimens were tested at each stress level. Guimaraes plotted a creep coefficient against the percentage of the initial stress level of the yarn, together with data of Kevlar ropes which had been tested earlier [3] (Fig. 11). He concluded that the creep coefficient is parallel to the *x*-axis above 50% ABL, which conforms to the linear visco-elastic behaviour of aramid. This result is in agreement with the present analysis, but it must be noted that Guimaraes' high-stress results were obtained from long-duration tests on parallel-lay ropes (which may be subject to bundle effects), while his lower stress results were obtained from short-duration tests on yarns. He found no significant effect due to pre-loading of the yarns.

The creep coefficient plotted by Guimaraes is the creep strain divided by the initial strain, divided again by $\log_{10}(t)$, where t is measured in seconds. His best fit solution for the creep coefficient was given as:

Table 3 Stress relaxation coefficient

Load level %ABL	Test 1	Test 2	Test 3	Test 4	Rope data
10	–	–	0.0461	0.0468	–
15	–	–	0.0403	0.0398	–
20	–	–	0.0336	0.0374	–
20	–	–	0.0338	0.031	–
25	–	–	0.0274	0.029	–
30	–	–	0.0233	0.0198	–
30	–	–		0.0229	–
35	–	–	0.0203	0.0173	–
36.5	–	–	–	–	0.024
40	–	0.0155	0.0177	0.0191	–
42.1	–	–	–	–	0.0266
45	–	0.0138	0.0131	0.0159	–
50	0.010335	0.0154	–	–	–
51.4	–	–	–	–	0.0174
55	0.010159	0.0122	–	–	–
60	0.009105	0.0115	–	–	–
63.6	–	–	–	–	0.0156
64.5	–	–	–	–	0.0173
65	0.009268	–	–	–	–
69.2	–	–	–	–	0.0183
70	0.009113	0.0115	–	–	–
70	–	0.01556	–	–	–
75	0.011596	0.0132	–	–	–
75	–	0.0104	–	–	–
80	0.009173	0.0117	–	–	–
80	–	0.0087	–	–	–

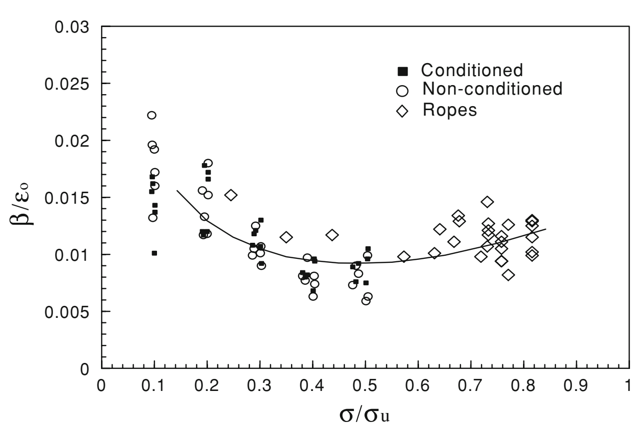

Fig. 11 Creep coefficient for Kevlar 49 yarns and ropes as reported by Guimaraes [18]

$$\frac{\beta}{\varepsilon_0} = \left[0.0041\left(\frac{\sigma}{\sigma_u}\right)^{-0.7} + 0.0106\left(\frac{\sigma}{\sigma_u}\right)^{3}\right] \quad (9)$$

This expression allows Guimaraes' best fit line to be compared with the values obtained here; his predictions (GBG) are shown for 10 h and 800 h on Fig. 10. It will be seen that they underestimate the creep compliance shown in the present tests, but show a similar variation between linear response at high loads and non-linear response at low loads.

Stress-relaxation tests

Stress-relaxation tests were carried out as described above. The results of the four tests are presented separately.

- *Test-01*: This test series lasted for about 1,600 h. Figure 12 shows the stress-relaxation curve for the test at 50% ABL. During the time periods marked 'a' & 'b' the temperature decreased; because aramids have a negative coefficient of thermal expansion the yarns would have slightly increased in length, and the steel reaction bars in the frame would have decreased in length. Both effects lead to a reduction in stress. The gap over time 'c' was due to a gap in the data-recording. This behaviour was observed for all the other tests carried out at the same time and the data over those regions were discarded in the analysis. It was assumed that no filaments were broken when the temperature changed.
- *Test-02*: This test series lasted for about 1,650 h. Figures 13 and 14 show stress versus time, and log-time, respectively. The plots show that relaxation is linear with log-time.
- *Test-03*: Test 3 lasted for 600 h but the data after 75 h had to be discarded because of temperature variation.
- *Test-04*: In this test, data after 1,200 h were discarded due to uncertainty about the relative humidity conditions.

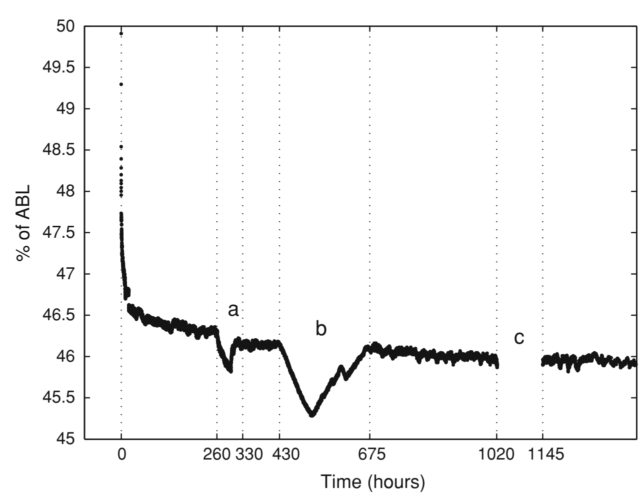

Fig. 12 Typical stress-relaxation response showing effect of temperature excursion

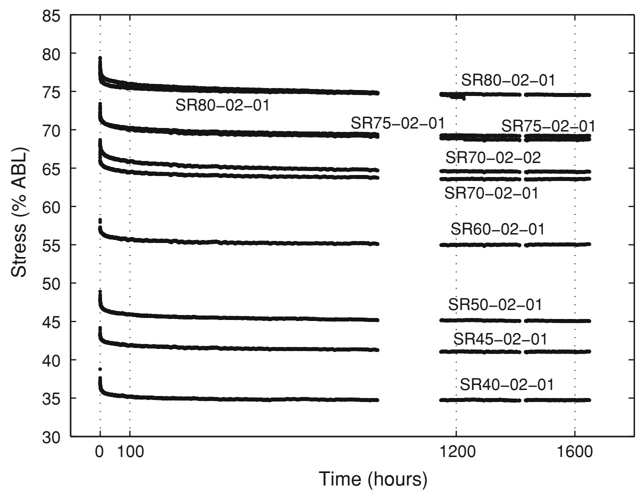

Fig. 13 Stress-relaxation response against time

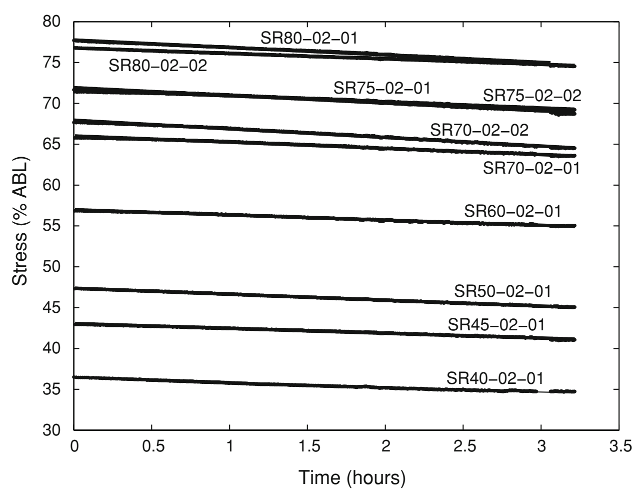

Fig. 14 Stress-relaxation response against log-time

Figure 15 shows the variation of the stress-relaxation coefficient for the four tests together with aramid rope data obtained by Amaniampong [6]. Because all the stress-relaxation tests results were linear with log time, there is no distinction between tests of different durations. Two distinct regions can be seen in the graph; the stress-relaxation coefficient λ varies with the initial stress for values less than 50% ABL. In contrast, when the initial stress values are greater than 50% ABL, no specific trend in λ can be seen; thus it can be deduced that the value of λ is stress independent, which implies the linear visco-elastic behaviour.

It is notable that the scatter is significantly lower for the stress-relaxation results than for the creep results shown in Fig. 10, especially at lower stress levels, but this may be because the relaxation coefficients have been calculated starting 1 h after the initial imposition of the load,

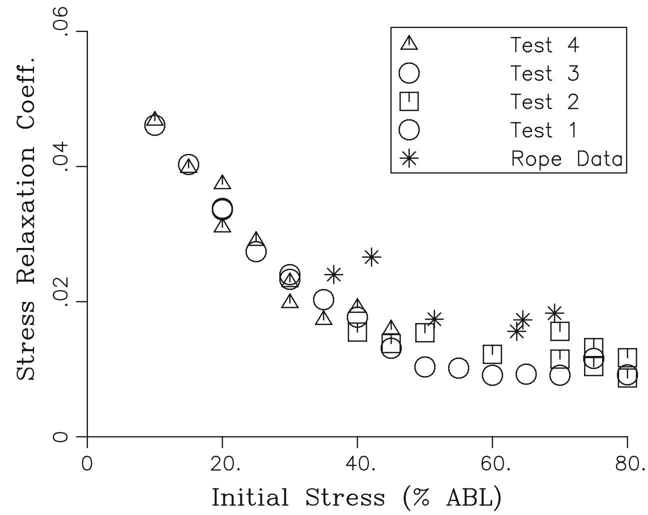

Fig. 15 Stress relaxation coefficients for all tests

following the earlier work [6, 7], whereas the creep coefficients include the immediate primary creep.

Conclusion

The uncertainty of the visco-elastic behaviour of Kevlar yarns in different stress regions has now been resolved. Creep and stress-relaxation tests carried out over a wide stress spectrum show that Kevlar possesses non-linear visco-elastic behaviour when the initial stress levels are less than about 40% ABL, but linear visco-elastic behaviour is apparent at stress levels above about 40% ABL.

It is not possible, from these results, to propose a mechanism for this change in behaviour, but it should be noted that the change appears to coincide with the change in stiffness on the stress–strain curve.

It would be interesting to repeat these tests at different temperatures to determine the activation energies of the visco-elastic processes involved. If these differed above and below the 40% ABL stress level, it would indicate that different physical processes were involved.

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