Creep and Strength Retention of Aramid Fibers

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ABSTRACT: Creep tests at ambient conditions have been carried out on Kevlar 49 and Technora yarns covering a wide stress spectrum (10–70% average breaking load) for a long period of time (up to a year). The results confirm that Kevlar 49 and Technora yarns show a nonlinear behavior at stresses below 40% of the breaking load and a linear behavior at stresses above 40%. The strength retention following creep for Kevlar 49 and Technora has also been examined. The results show a significant difference in the behavior of the two materials. Kevlar 49 appears to lose strength almost linearly with time, while Technora seems to lose strength much more rapidly. These results would have significant implications for design. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 126: 91–103, 2012

Key words: viscoelasticity; creep testing; creep compliance; strength retention; Kevlar 49; Technora

INTRODUCTION

Aramid fibers have considerable potential for use as tension elements in structural engineering, either as prestressing tendons for concrete or stay cables for bridges. These applications are often characterized by high permanent loads. Aramid fibers show low creep (typically less that 0.1% strain in service) but this can be significant if it leads to a loss of prestressing force or a redistribution of forces between cables. There is also a major issue associated with stress-rupture since, to be used economically, as much force as possible needs to be applied in the permanent state. Determining a limit that can be applied with confidence is of crucial importance.

Even in applications such as prestressed concrete, where the force in the tendon changes very little under normal loading, there is a requirement that the tendon should not snap when subjected to a major overload. So there is often also a requirement for knowledge of the short-term strength after a period of creep.

The viscoelasticity of aramids has been the subject of some discussion; various researchers[1–4] have been working in this field. Until recently it was not even clear whether the material behaved linearly or nonlinearly. Stress relaxation tests tended to show linear behavior, whereas creep tests showed nonlinear behavior. However, Burgoyne and Alwis[5] noted that the creep tests were normally carried out while determining stress-rupture lifetimes (and thus were carried out at high stress levels), whereas stress-relaxation tests were carried out at normal operating stresses, which are much lower. Burgoyne and Alwis carried out both creep and stress-relaxation tests over a full range of loads, and showed that the material behaves differently at stresses above and below 40% of the short-term strength.

While convincing, Burgoyne and Alwis' tests were limited. Most of their creep tests did not extend much beyond 800 h, and they only tested one yarn (Kevlar 49). But they did apply a new accelerated test method (the Stepped Isothermal Method—SIM) to aramids for the first time,[6] and this opened the way to much faster ways of producing creep and stress-rupture data.

The work described here forms a part of an extension to that study aimed at producing reliable estimates of the creep-rupture lifetimes that could be used by practicing engineers. An extensive program of testing was carried out using SIM on two different aramid fibers (Kevlar 49 and Technora)[7] and a new test method was developed that uses stress rather than temperature to accelerate creep (Stepped Isostress Method—SSM).[8] Implications for structural design have also been presented.[9]

This accelerated testing work needed to be correlated with creep data obtained in real time, by the application of dead loads, so a program of creep testing with load durations of 1 year were carried out. That testing program is the main subject of this article. But the test program also provided the

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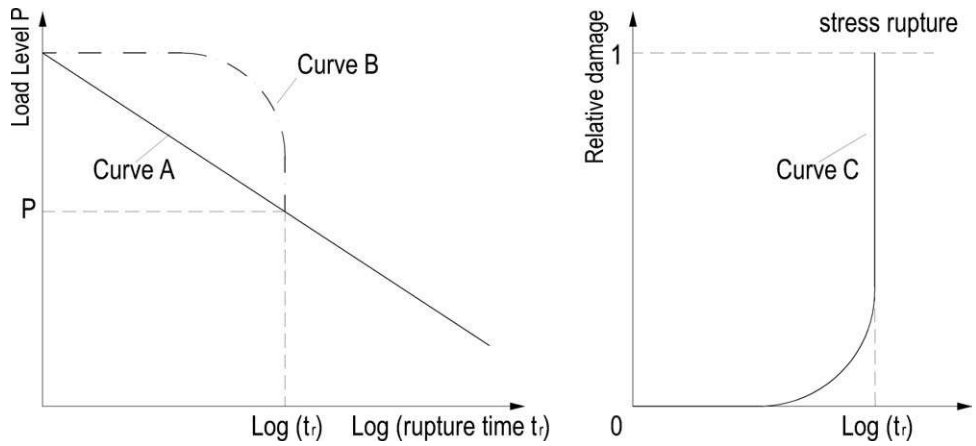

Figure 1 Creep-rupture (Curve A), residual strength (Curve B), and relative damage (Curve C) for aramid fibers.

opportunity to study the retained strength after creep has taken place, which is what governs the capacity of a structure when subjected to a rare overload.

The fixed load that can be sustained for a given period of time defines the stress-rupture lifetime; for aramid fibers this is usually presented as a linear relationship between load and the logarithm of the time to failure (Curve A in Fig. 1). However, if many specimens are loaded with a force P and then subsequently tested at different ages, up to the predicted rupture time t_r, the short-term retained strength can be expected to be higher (Curve B in Fig. 1), but by how much is unknown.

If the shape of Curve B (or even its existence) are not known, practicing engineers are effectively forced to use Curve A as though it also represented the short-term strength. The effect is that the stress limit applied to occasional loads toward the end of the structure's lifetime is the same as that applied to permanent loads. This significantly reduces the permanent load that the fibers can carry, which imposes a large financial penalty on the use of aramids, with the result that they are rarely used.

There has been relatively little work on the determination of retained strength. Gerritse and Den Uijl,[10] examined the long-term behavior of Arapree (Twaron) and showed that the retained strength did not change significantly until just before rupture due to creep was expected. Rostasy and Scheibe[11] proposed an engineering model for the creep-rupture, residual strength, and relative damage versus time under constant stress. They illustrated schematically the relative damage of the fiber (Curve C in Fig. 1). Damage grows rapidly as the rupture time is approached. However, both Gerritse's and Rostasy's testing involved exposing the fibers to environmental conditions (alkaline water) that would themselves have caused a reduction in strength. The activation energy of the hydrolytic reaction will be different from that relating to creep, so it is impossible to disentangle the two effects from this earlier testing.

It is expensive and time-consuming to determine retained strength. A series of tests have to be carried out subjecting the fiber to a creep load, and after a pre-determined time it has to be tested for failure. This normally requires two different testing machines, since machines suitable for tension testing cannot usually be dedicated to long-term creep tests.

As part of the test program described above, a large number of dead-weight creep rigs were built. These were built with demountable end clamps that also fitted into the tension testing machine, which meant that the fibers did not need to be handled directly while being transferred between the creep and tension testing rigs. Toward the end of the creep test program, a number of these creep rigs became available, which allowed a limited number of strength retention tests (SRT) to be carried out.

The sections below describe both the conventional creep tests (CCT) and the subsequent retained strength tests.

MATERIALS AND EXPERIMENTAL SET-UP

Kevlar 49 and Technora yarns were used for all tests. They were supplied in the form used for rope manufacture, having been twisted and rewound.

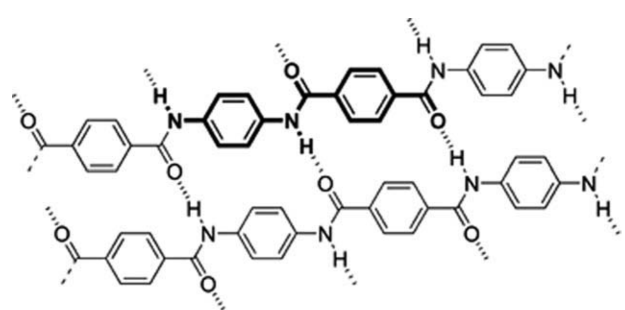

Figure 2 Chemical structure of Kevlar 49.

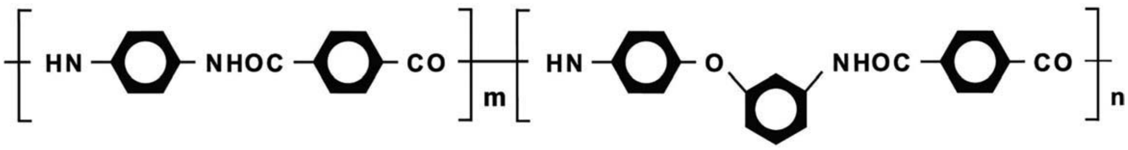

Figure 3 Chemical structure of Technora.

Kevlar 49 is an aramid fiber made by Du Pont from a single monomer unit. Its chemical structure consists of aromatic polyamides containing chains of aromatic rings, linked together with —CO— and —NH— end groups, weakly linked with hydrogen bonds between adjacent long chain molecules. Figure 2 illustrates the molecular structure of Kevlar 49. The bold lines denote the repeating unit in a molecule and the dashed lines denote the hydrogen bonds. Technora is a copolymer, made by Teijin; its chemical structure consists of two different monomer units, which are placed in a completely random sequence in the polymer chain. One of the monomer units is the same as Kevlar, while the other contains an extra benzene ring. Figure 3 illustrates the molecular structure of Technora. The symbols "*m*" and "*n*" denote mol%, and always $(m + n) = 100\%$.

The cross-sectional area (A) of the yarns, after removing moisture, was found to be 0.175 mm^2 and 0.123 mm^2, respectively. The breaking load of Kevlar 49 and Technora was determined from 20 short-term tensile tests. From the dispersion of results, a mean value μ_P and a standard deviation σ_P were determined. The measured values shown in Table I are in agreement with the values given by the two manufacturers,[12,13] allowing for the rewinding. All subsequent stress levels will be expressed as a percentage of this average breaking load (ABL). Before testing, the yarn reels were kept at constant room temperature (25°C) and humidity (50% relative humidity), and placed in a black polythene bag inside a box to protect them from ultraviolet light.

TABLE I
Mean Value μ_P and Standard Deviation σ_P of the Breaking Load

Material	Mean value μ_P [N]	Standard Deviation σ_P [N]
Kevlar 49	444.60	8.22
Technora	349.01	6.75

Two different types of testing for the yarns are described:

- Conventional creep tests (CCT) at different stress levels under constant temperature and humidity.
- Strength retention tests (SRT)

Because many end clamps were required, conventional horn grips could not be used. Specially developed end clamps were used that could be manufactured cheaply. The yarn is wrapped around a spindle and then fixed by a grip (Figs. 4 and 5). An extensive test program was undertaken to determine the jaw effect and to ensure that failure took place in the gauge length, and not in the jaws.[14] Similar clamping arrangements were used for short-term, accelerated creep, and stress relaxation tests.

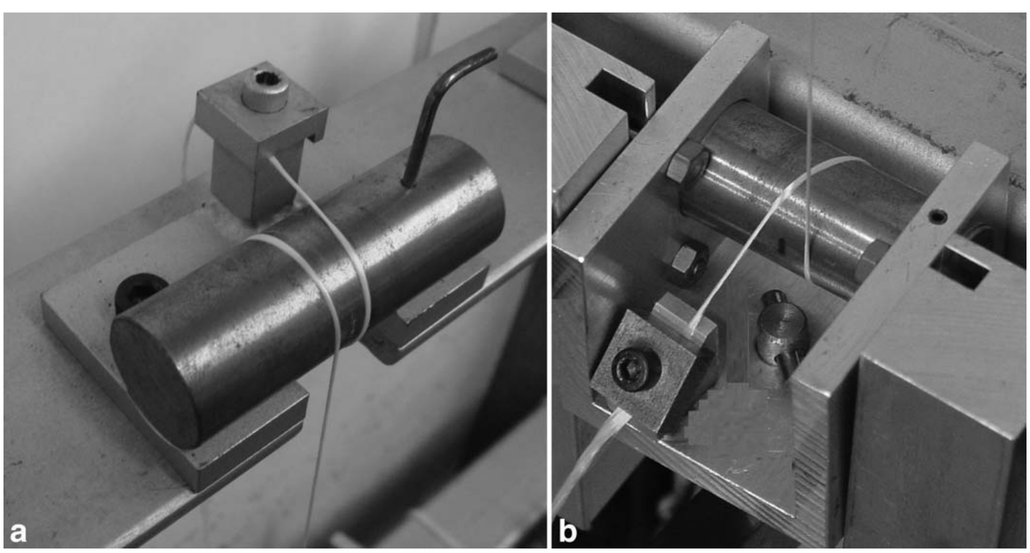

Figure 4 Top and bottom clamp of a conventional creep test.

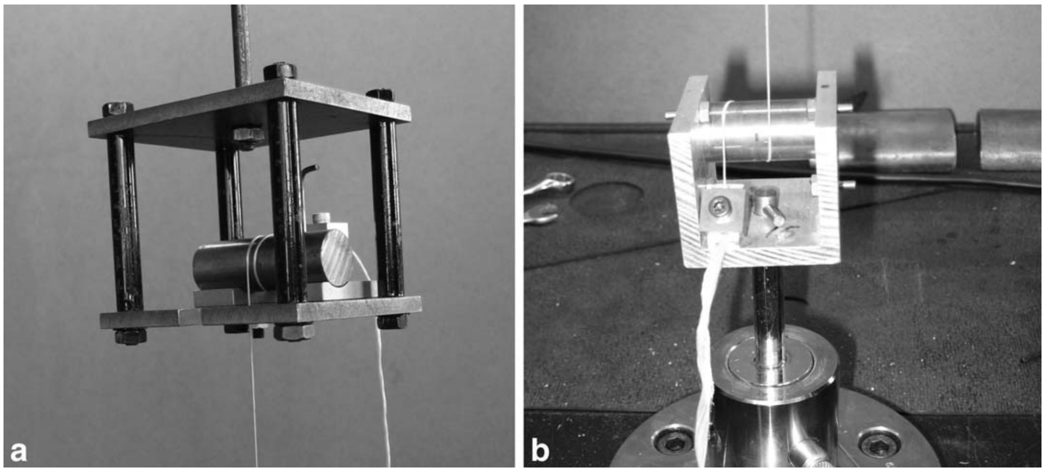

Figure 5 Top and bottom clamp of a strength retention test.

One of the important features of the clamp design was that they could be moved from the creep rig (Fig. 4) to the tension testing machine (Fig. 5) while still attached to the specimen. This was an extremely delicate process and great care had to be taken not to put a sudden additional force on the yarn or to slacken the yarn so that there is a movement around the spindles at the support. The great advantage of this system is that the yarn itself was only handled when it was first put into the creep rig, not when it was transferred to the tension machine.

CCT were carried out in a special room where the temperature and humidity levels were controlled by an air-conditioning system (Fig. 6). Eighteen clamping devices were used. The top clamp was kept stationary and the lower clamp was free to move vertically between two metal rails, as shown in Figure 4. Each yarn was subjected to a constant load by hanging dead-weights through a lever arm at the bottom clamp. Mechanical strain gauges of circular form were used to measure the elongation of the yarns, and the logger was fitted with an uninterruptible power supply (UPS).

In the SRT, the two clamps (Fig. 5) were fixed to the tension testing machine by means of two Invar bars. The load was applied by moving the cross-head of the testing machine at a constant rate and was measured by a 1 kN load cell (Fig. 7). The cross-head movement was measured by a displacement transducer with an accuracy of 0.001 mm. The load cell and the displacement transducer were

Figure 6 Experimental set-up for CCT tests.

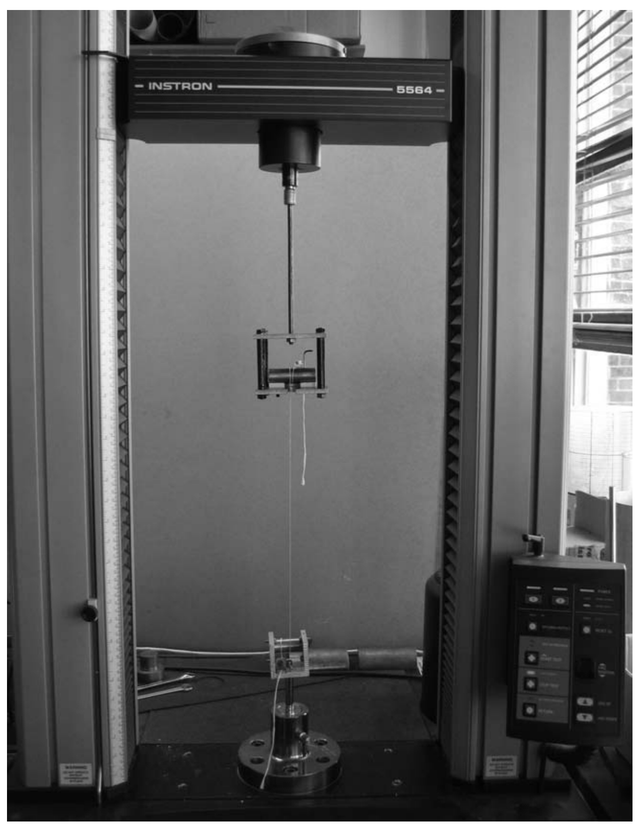

Figure 7 Experimental set-up for SRT.

TABLE II
Creep Test Plan and Creep Compliance Values at Different Times for All Load Levels (Kevlar 49)

		Creep compliance $\varphi(t)$ (= $\varepsilon_c(t)/\sigma$)					Time t (h)		
	Test label	φ(10)	φ(50)	φ(200)	φ(800)	φ(1500)	φ(2400)	φ(4800)	φ(8760)
Kevlar 49 fibers	CCTK-10-01	0.00415	0.00618	0.00748	0.00947	0.01085	0.01174	–	–
	−02				DAMAGED				
	−03	0.00563	0.00669	0.00798	0.00851	0.00871	0.00899	0.01005	0.01141
	CCTK-20-01	0.00263	0.00432	0.00575	0.00665	0.00727	0.00769	–	–
	−02	0.00221	0.00380	0.00496	0.00627	0.00683	0.00749	–	–
	CCTK-30-01	0.00287	0.00401	0.00456	0.00525	0.00562	0.00593	–	–
	−02	0.00153	0.00257	0.00333	0.00411	0.00442	0.00479	–	–
	CCTK-40-01	0.00077	0.00134	0.00175	0.00224	0.00236	0.00250	–	–
	−02				DAMAGED				
	−03	0.00146	0.00174	0.00207	0.00234	0.00239	0.00247	0.00264	0.00302
	CCTK-50-01	0.00122	0.00159	0.00182	0.00212	0.00225	0.00237	–	–
	−02	0.00135	0.00187	0.00210	0.00223	0.00229	0.00227	–	–
	−03	0.00136	0.00161	0.00192	0.00216	0.00226	0.00232	0.00251	0.00293
	−04	0.00143	0.00167	0.00182	0.00202	0.00213	0.00223	0.00251	0.00287
	CCTK-55-01	0.00159	0.00197	0.00219	0.00228	0.00233	0.00237	–	–
	−02	0.00104	0.00146	0.00179	0.00211	0.00217	0.00232	–	–
	−03	0.00126	0.00157	0.00191	0.00211	0.00225	0.00230	0.00244	0.00265
	−04	0.00158	0.00184	0.00199	0.00225	0.00225	0.00227	0.00228	0.00245
	CCTK-60-01	0.00113	0.00138	0.00153	0.00170	0.00178	0.00188	–	–
	−02	0.00111	0.00133	0.00153	0.00172	0.00178	0.00189	–	–
	CCTK-65−01				DAMAGED				
	−02	0.00114	0.00134	0.00147	0.00155	0.00166	0.00167	–	–
	−03	0.00111	0.00137	0.00151	0.00161	0.00165	0.00168	0.00166	0.00174
	CCTK-70−01				DAMAGED				
	−02	0.00086	0.00118	0.00145	0.00179	0.00190	0.00205	–	–
	−03	0.00123	0.00145	0.00159	0.00176	0.00182	0.00182	0.00193	0.00226
	−04	0.00116	0.00134	0.00152	0.00171	0.00178	0.00182	0.00191	0.00208

TABLE III
Creep Test Plan and Creep Compliance Values at Different Times for All Load Levels (Technora)

		Creep compliance $\varphi(t)$ (= $\varepsilon_c(t)/\sigma$)					Time t (h)		
	Test label	φ(10)	φ(50)	φ(200)	φ(800)	φ(1500)	φ(2400)	φ(4800)	φ(8760)
Technora fibers	CCTT-10-01	0.01309	0.01588	0.01832	0.02053	0.02172	0.02315	–	–
	−02	0.01306	0.01622	0.01838	0.02044	0.02136	0.02250	–	–
	CCTT-20-01	0.00650	0.00807	0.00915	0.00944	0.00984	0.01015	–	–
	−02	0.00627	0.00778	0.00889	0.00988	0.01050	0.01088	–	–
	−03	0.00605	0.00769	0.00919	0.01086	0.01141	0.01180	0.01276	0.01404
	CCTT-30-01	0.00413	0.00503	0.00567	0.00576	0.00592	0.00599	–	–
	−02	0.00414	0.00504	0.00560	0.00596	0.00627	0.00646	–	–
	−03	0.00405	0.00479	0.00553	0.00633	0.00667	0.00687	0.00725	0.00773
	CCTT-40-01	0.00306	0.00345	0.00363	0.00382	0.00392	0.00400	–	–
	−02	0.00286	0.00326	0.00348	0.00357	0.00375	0.00391	–	–
	CCTT-50-01	0.00220	0.00218	0.00236	0.00266	0.00275	0.00278	–	–
	−02	0.00220	0.00234	0.00246	0.00256	0.00261	0.00271	–	–
	−03	0.00180	0.00226	0.00269	0.00314	0.00337	0.00347	0.00367	0.00394
	CCTT-55−01				DAMAGED				
	−02	0.00209	0.00238	0.00265	0.00291	0.00304	0.00319	–	–
	−03	0.00190	0.00251	0.00289	0.00298	0.00307	0.00302	0.00316	0.00313
	CCTT-60−01				DAMAGED				
	−02				DAMAGED				
	−03	0.00166	0.00201	0.00232	0.00257	0.00272	0.00277	0.00296	0.00308
	−04	0.00168	0.00207	0.00242	0.00266	0.00285	0.00290	0.00312	0.00336
	CCTT-65-01	0.00142	0.00149	0.00189	0.00194	0.00202	0.00208	–	–
	−02				DAMAGED				
	−03	0.00147	0.00161	0.00189	0.00202	0.00213	0.00217	0.00233	0.00234
	−04	0.00192	0.00219	0.00232	0.00246	0.00260	0.00266	0.00286	0.00309
	CCTT-70−01				DAMAGED				
	−02	0.00197	0.00223	0.00237	0.00244	0.00255	0.00262	–	–
	−03				DAMAGED				

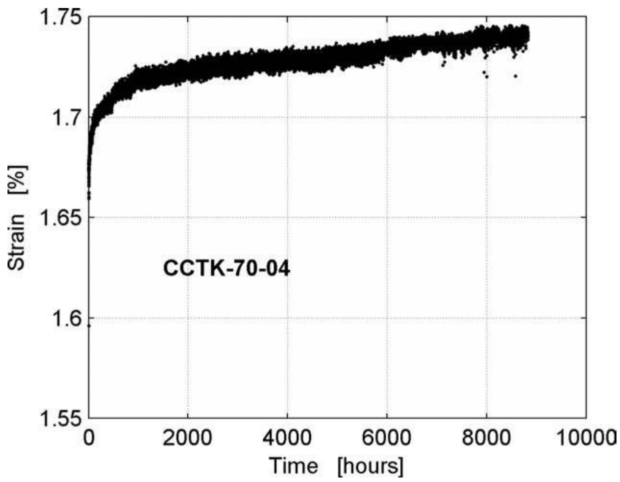

Figure 8 A typical strain vs. time curve (CCTK-70-04).

connected to a data logger and readings were taken at small time intervals.

Testing procedure

Creep tests

The creep rigs were installed in a room that could heat but not cool the temperature, and could maintain the humidity at a desired level. It was thus decided to keep the temperature just above the temperature elsewhere within the laboratories at 25°C and to maintain the humidity at 50% relative humidity (RH). All yarns had a nominal length of 350 mm and were fitted with spring steel mechanical strain gauges. A constant load was applied to each yarn by hanging dead-weights through a lever arrangement at the bottom clamp. The dead-weights were initially supported on small scissors-jacks that could be lowered slowly to avoid shock loading.

The above procedure was followed for testing several specimens at each load level: 10, 20, 30, 40, 50, 55, 60, 65, and 70% of ABL. Experiments were not conducted above 70% ABL, since creep-rupture failure would be expected within the test period[7,15] which could have caused vibrations that would have damaged the other specimens. A schedule of all CCT tests carried out is given in Table II for Kevlar 49 and in Table III for Technora. Each test is identified by a test label, e.g. CCTT-70-02, where "CCT" denotes conventional creep tests, "T" denotes Technora ("K" for Kevlar), "70" denotes the load level, "02" denotes the repetition of the test. The first and second repetitions lasted for 100 days, while the third and fourth repetitions were extended to 1 year. All the strain gauges, the room thermocouple, and the room humidity sensor were connected to a data logger and readings were taken every 10 min and saved directly to a computer.

Burgoyne and Alwis[5] proposed a practical method to assess viscoelasticity of Kevlar 49 fibers; they plotted creep compliance values [$\varphi(t)(=\varepsilon_c(t)/\sigma)$] vs. stress ($\sigma$) at different times to check whether a material is linearly viscoelastic. If the points for a stress range fit on a straight line parallel to the σ axis, the creep compliance is constant which implies that the material is linearly viscoelastic for this stress range and that specific time t_0. On the other hand, materials whose strain at any state is a function of both time and stress are defined as nonlinear viscoelastic materials.

Strength retention tests

Two types of strength retention test were carried out. The first, tested the remaining tensile strength of the yarns that had been loaded for a year in the creep tests. These showed interesting results so a second set was undertaken in the limited time available at the end of the project. Tests were carried out at 70% ABL for Kevlar 49 and 65% ABL for Technora were carried out for various creep times (1 week to 3 months) and then tested to failure.

RESULTS AND DISCUSSION

Creep tests

The obtained readings were used to plot the corresponding strain vs. time curves. These curves from all tests on Kevlar and Technora are given elsewhere.[16] A typical creep strain vs. time curve is given for test CCTK-70-04 (Fig. 8). The observed scatter in the curves is due to the inherent noise of the measuring equipment (accuracy of strain gauges ±0.0003); for calculation purposes, in order to diminish this noise, the value of strain at any time is that corresponding to the center of the spread (mean value).

The shape of all strain vs. time curves is similar, showing a primary creep region that levels out and a secondary creep region which starts at about 1000 h and is almost linear with a constant slope. No tertiary

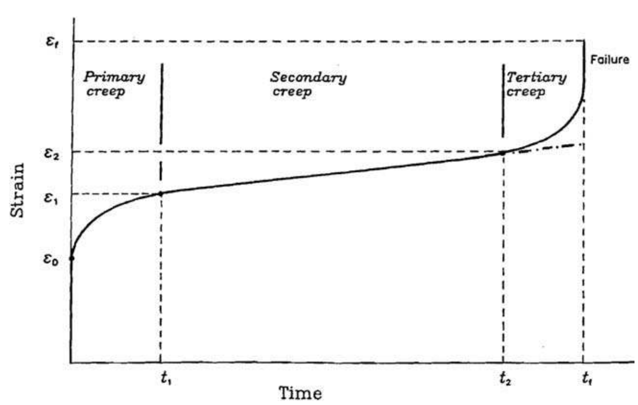

Figure 9 Schematic creep curve (Guimaraes, 1988).

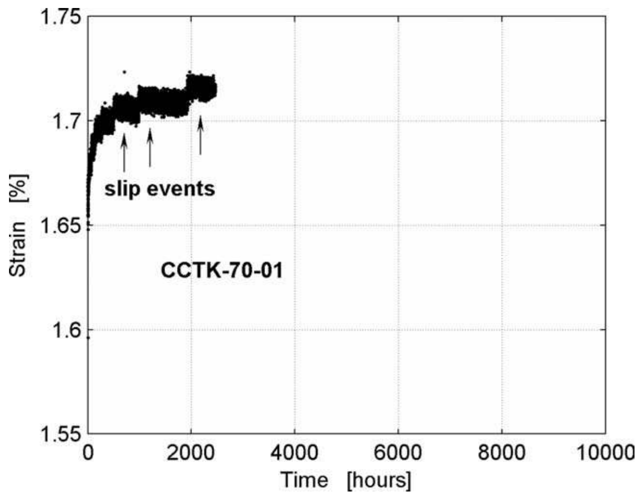

Figure 10 A typical abandoned strain vs. time curve (CCTK-70-01).

region is present since all creep tests were stopped at 100–365 days, and the tertiary region at 70% ABL is expected to start at about 5 years.[7,9] It can be observed that the shape of the curves is in general agreement with those found from CCT on parallel-lay aramid ropes, at various load levels (25–82% nominal breaking load (NBL)), carried out by Chambers[17] and Guimaraes.[18] The general form of these curves is shown in Figure 9.

Some creep tests, for example test CCTK-70-01 (Fig. 10), had to be discarded, because slip events were observed. These were caused by slip between the mechanical strain gauge and the yarn or due to a sudden change of the testing room temperature (when visiting the room), which caused small jumps in the creep curves. Although the strain vs. time curves of these damaged tests are presented, they were ignored in all further plots and calculations.

The biggest issue for long-term testing is to maintain the temperature and humidity constant. Many researchers in the past have attempted creep testing for long period of time, but had temperature and/or humidity variations, which affected their results. The temperature and humidity variation with time in the testing room is shown in Figure 11 and it verifies that they were kept practically constant throughout the testing period.

All creep curves (strain vs. $\log_{10}(t)$) for Kevlar 49 (Sets 1–4) are plotted in Figure 12. The corresponding creep curves for Technora (Sets 1–4) are plotted in Figure 13. It is observed that the creep curves are practically straight on a logarithmic time scale, which agrees with other work[18–21] that also concluded that creep of aramid fibers follows a logarithmic function of time.

To check the viscoelasticity of Kevlar 49 and Technora, creep compliance $\varphi(t)$ values are calculated for each test at different elapsed times t_0 (= 10, 50, 200, 800, 1500, 2400, 4800, and 8760 h). All values are given for Kevlar 49 in Table II and plotted in Figure 14; for Technora they are in Table III and plotted in Figure 15.

These figures, which include all creep compliance values from all tests for both materials, are very similar to results produced for much shorter time scales by Burgoyne and Alwis,[5] and similar conclusions can be reached.

(a) At any stress level, creep compliance $\varphi(t)$ increases with elapsed time t_0.
(b) For the stress range 40–70% ABL, and at every elapsed time t_0, the creep compliance $\varphi(t)$ values fit practically on a straight line parallel to the σ axis. This means that the creep compliance is constant at every elapsed time t_0 and implies that both materials are linearly viscoelastic for this stress range.
(c) For stresses lower than 40% ABL, and for all elapsed time t_0, the creep compliance $\varphi(t)$ values increase with decreasing stress level, which means that the materials will creep

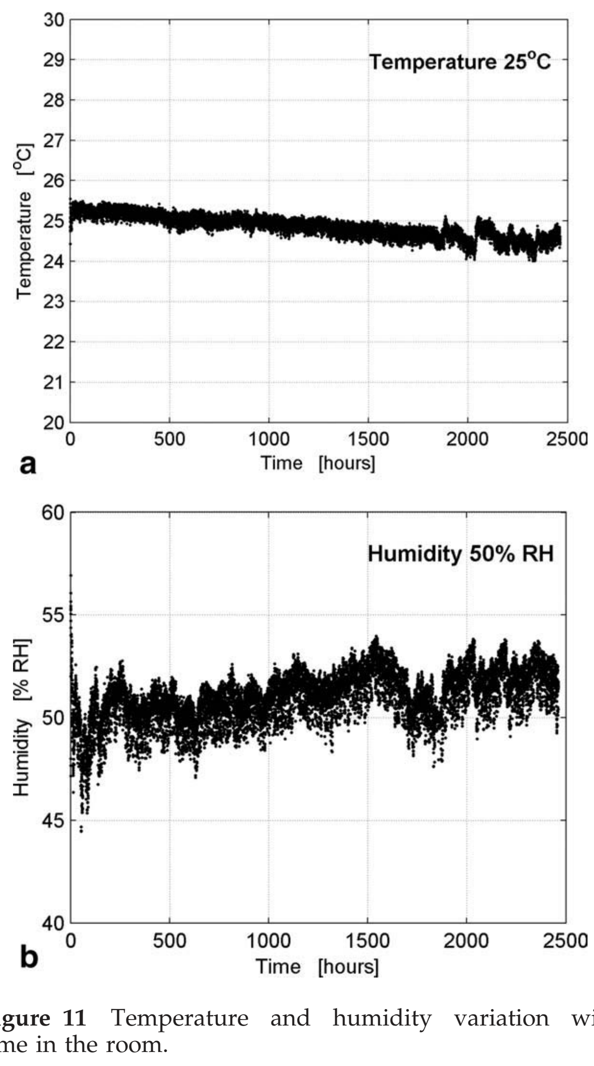

Figure 11 Temperature and humidity variation with time in the room.

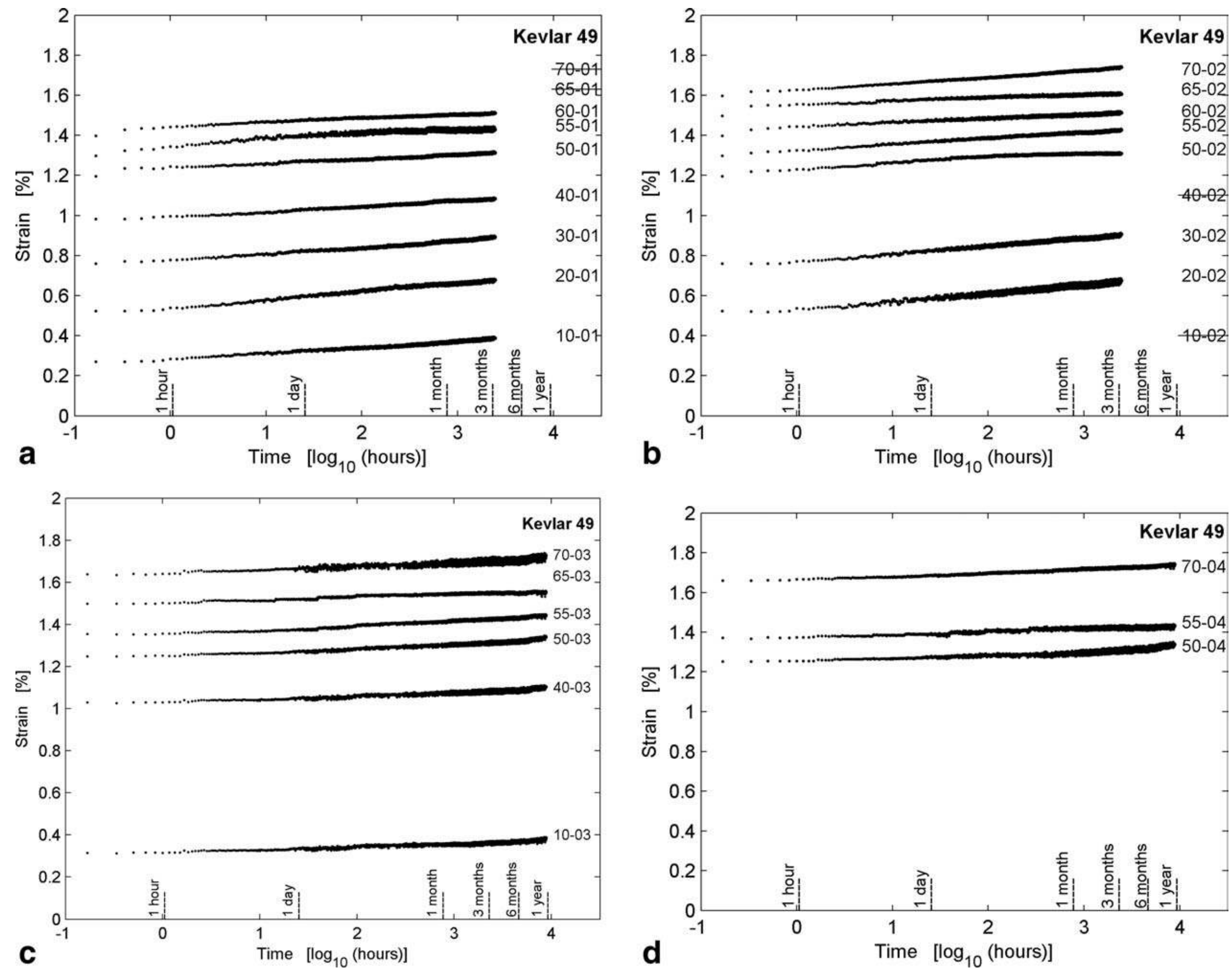

Figure 12 (a) Creep curves for Kevlar 49 (Set 1). (b) Creep curves for Kevlar 49 (Set 2). (c) Creep curves for Kevlar 49 (Set 3). (d) Creep curves for Kevlar 49 (Set 4).

faster at lower stress levels. Therefore both materials exhibit nonlinear creep behavior below 40% ABL. Because the creep compliance is normalized by dividing by the applied stress, the total creep strain for materials at low stress levels does not exceed the creep strain at higher loads.

(d) Kevlar 49 and Technora yarns differ chemically, but they show similar viscoelastic behavior; the creep compliance $\varphi(t)$ values for Technora are slightly higher than the corresponding ones for Kevlar 49.

Similar work was performed by Guimaraes[22] to understand the viscoelastic behavior of Kevlar 49 yarns. He carried out two sets of creep testing at five different stress levels (10%, 20%, 30%, 40%, and 50%) at a constant temperature of 25°C ± 2.5°C and humidity of 75% ± 7% for a short period of time (72 h). The principle objective of his tests was to see whether specimens that had been conditioned by exposure to a brief pre-load showed different creep behavior. Six specimens were tested at each stress level. He plotted the creep coefficient values vs. the percentage of the initial stress level of each specimen at various elapsed times; the creep coefficient is defined as the ratio of the creep strain over the initial strain times the log time (in sec). Together with the results obtained from the creep testing (loads up to 50%), he included test data of Kevlar ropes that had been tested in earlier work at higher stress levels for a longer time period. His best fit expression for the creep coefficient was given as:

$$\frac{\beta}{\varepsilon_0} = [0.0041(\frac{\sigma}{\sigma_0})^{-0.7} + 0.0106(\frac{\sigma}{\sigma_0})^3] \quad (1)$$

This best fit equation can be re-written as an expression of creep compliance and compared with the results found in the present study.

$$\varphi(t) = [0.0041(\frac{\sigma}{\sigma_u})^{-1.7} + 0.0106(\frac{\sigma}{\sigma_u})^2] \cdot \varepsilon_0 \cdot \log_{10} t \quad (2)$$

His predictions are shown for 10 and 8760 h on Figure 16(a) with the results of the present work. It can be

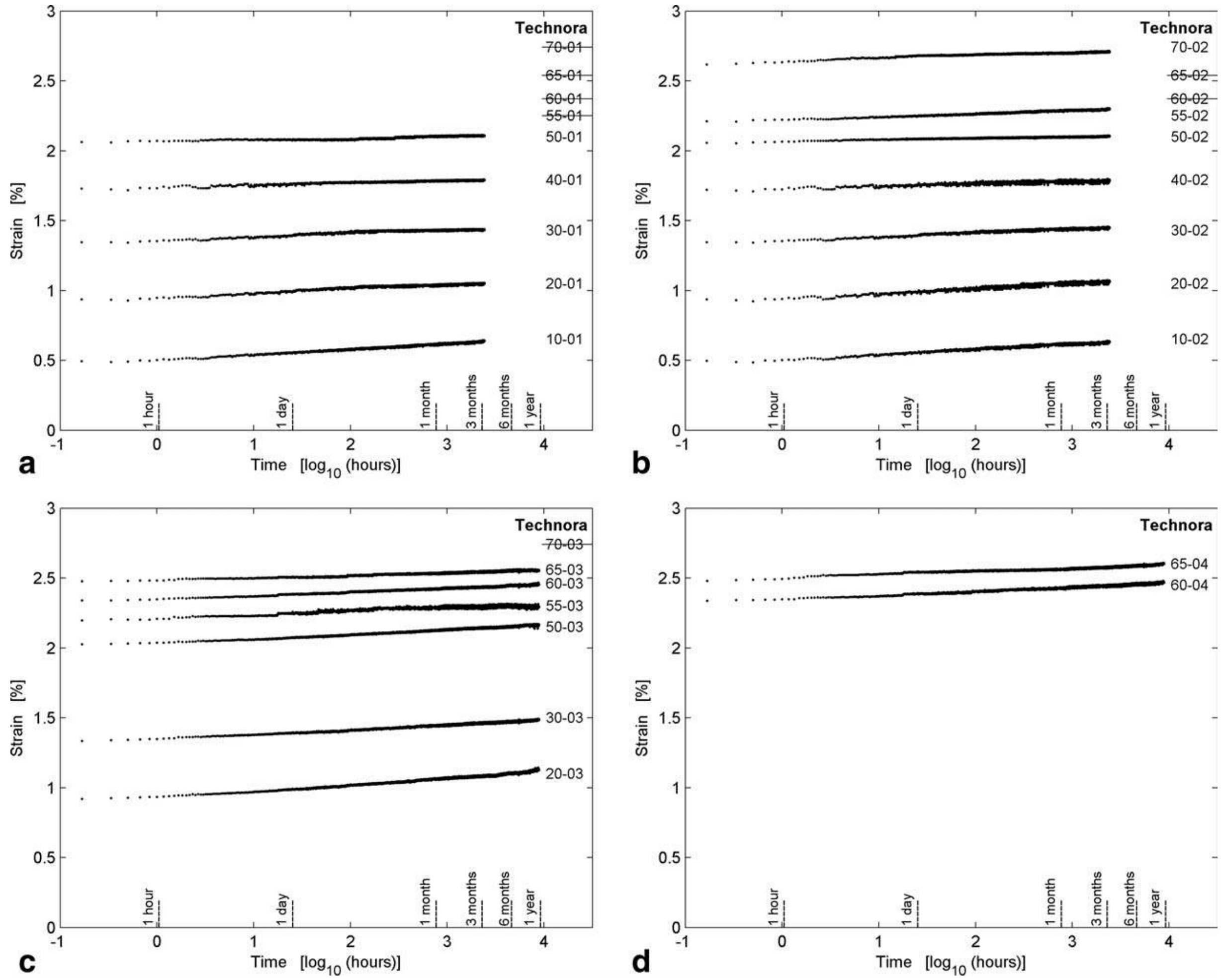

Figure 13 (a) Creep curves for Technora (Set 1). (b) Creep curves for Technora (Set 2). (c) Creep curves for Technora (Set 3). (d) Creep curves for Technora (Set 4).

observed that the predicted Guimaraes line is well below the values obtained in the present work. Guimaraes' tests were at higher humidity (75% RH); he used a mixture of ropes and yarns; his tests only lasted 72 h, and they were pre-loaded specimens, determination of the effect of which was the object of his study. It

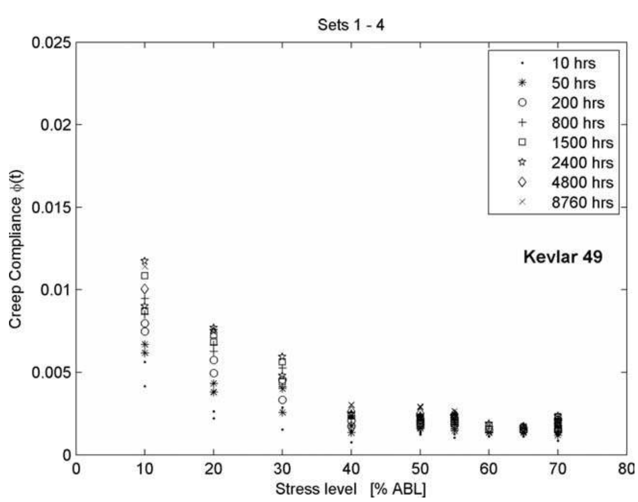

Figure 14 Creep compliance vs. stress level at diff. times for Kevlar 49 (Sets 1–4).

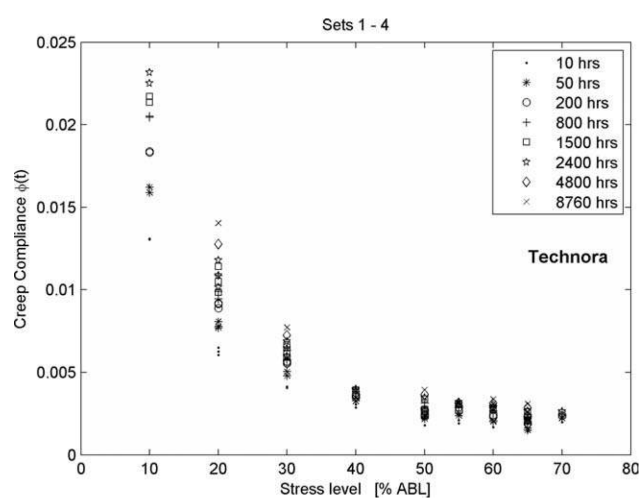

Figure 15 Creep compliance vs. stress level at diff. times for Technora (Sets 1–4).

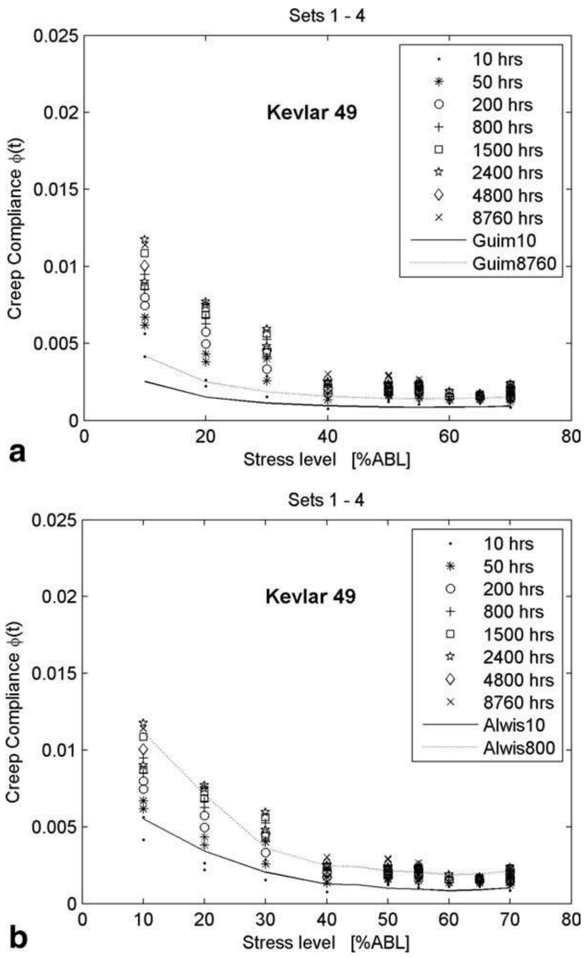

Figure 16 Creep compliance data at different times for Kevlar 49 (from the current work) compared with Guimaraes[22] and Burgoyne and Alwis[5] data.

appears from this that pre-loading may decrease the rate of creep, but it is notable that Guimaraes' responses follow a similar form to that seen here.

Alwis' test results for 10 and 800 h are shown in Figure16(b). They match the current results well.

Strength retention tests

SRT were performed on Kevlar 49 and Technora specimens that had been tested for 1 year. The failure loads are summarized in Tables IV and V for Kevlar 49 and Technora respectively, and plotted in Figure 17. The two materials clearly behave differently.

For Kevlar 49, all the retained strengths are in the range 95%–100% for loads up to 65% ABL, but it drops notably at 70% ABL. The expected time to rupture if subjected to a permanent load of 70% ABL is about 3.4 years[7,9] so it is perhaps unsurprising that the retained strength drops after 1 year.

The retained strength for Technora seems to drop more rapidly as the load increases, and at 65% ABL the retained strength has reduced to 86% of its initial value. At first sight, this looks similar to the Kevlar result, but the creep-rupture lifetime of Technora at 65% ABL is about 2200 years, so 1 year represents only a tiny fraction of the expected lifetime.

As a result of these observations, it was decided to carry out a series of SRT where the load is kept constant but the duration varies. 70% ABL was chosen for Kevlar 49 and 65% for Technora since these loads gave similar and significant reductions in retained strength over 1 year. Additional creep tests were carried out with durations from 4 days to 3 months following which the retained strength was measured (Table V).

All retained strength values (R) at various creep times are plotted on both logarithmic and linear time scales, together with accelerated and conventional and creep-rupture test data (P)[7] in Figures 18 and 19. The strength retention values are then fitted to appropriate curves.

As with the 1 year tests there is a significant difference between the two materials. For Kevlar 49, the retained strength appears to reduce almost linearly with time down to the creep-rupture lifetime. The best fit line is given by

TABLE IV
Strength Retention Tests After 1 Year of Creep at Various Load Levels for Kevlar 49 & Technora

	Creep period [days]	Retained load [N]	Retained load [% ABL]		Creep period [days]	Retained load [N]	Retained load [% ABL]
	Kevlar 49				Technora		
K10-03	368	427.29	96	T20-03	368	336.87	97
K40-03	368	443.28	100	T30-03	368	341.64	98
K50-03	368	429.19	96	T50-03	368	318.58	91
K50-04	368	430.15	97	T55-03	368	320.20	92
~~k55-03~~	~~368~~	~~361.76~~	~~81~~	T60-03	368	316.30	91
K55-04	368	430.47	97	T60-04	368	302.45	87
K65-03	368	427.95	96	T65-03	368	309.17	89
K70-03	368	396.12	89	T65-04	368	305.20	87
K70-04	368	381.65	86				

(K55-03 was damaged while being transferred from the creep rig to the tensile rig and for that reason is discarded).

TABLE V
Strength Retention After Creep at Various Load Levels and Times for Kevlar 49 & Technora

	Creep period [days]	Retained load [N]	Retained load [% ABL]		Creep period [days]	Retained Load [N]	Retained Load [% ABL]
	Kevlar 49				Technora		
K70-05	4	432.06	97	T65-05	10	329.47	94
K70-06	4	442.75	99	T65-06	10	325.28	93
K70-07	15	431.47	97	T65-07	20	330.68	95
K70-08	15	439.27	99	T65-08	20	323.77	93
K70-09	30	437.26	98	T65-09	30	328.80	94
K70-10	30	414.62	93	T65-10	45	321.07	92
K70-11	45	429.68	97	T65-11	45	322.78	92
K70-12	45	423.56	95	T65-12	45	312.52	90
K70-13	45	426.68	96	Short-term	0	349.01	100
K70-14	60	415.71	93	Long-term	793,942	226.85	65
K70-15	60	413.59	93				
K70-16	90	423.46	95				
K70-17	90	409.30	92				
K70-18	90	412.78	93				
K70-19	120	407.77	92				
K70-20	120	397.87	89				
Short-term	0	444.60	100				
Long-term	1230	311.50	70				

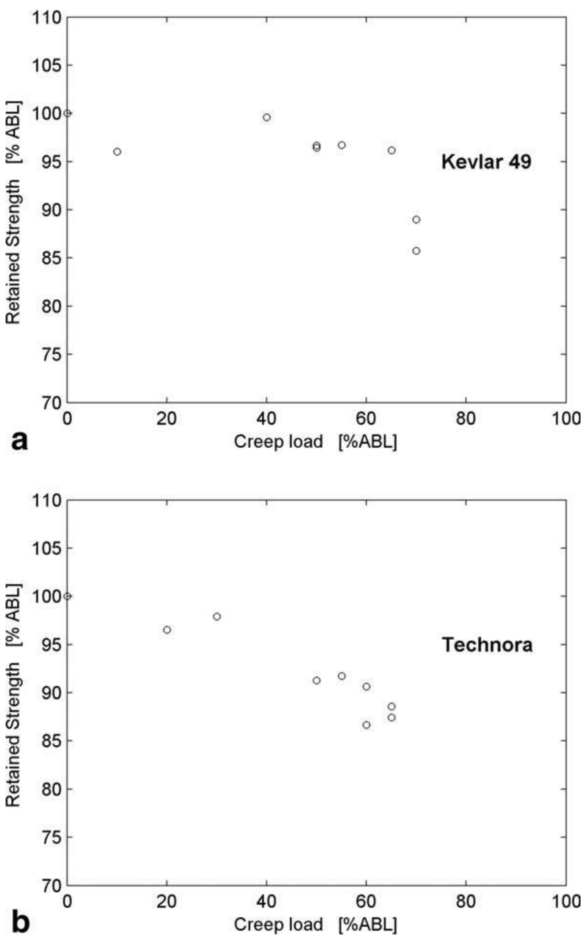

Figure 17 Retained strength vs. creep load after 1 year of creep for Kevlar 49 and Technora.

$$R = 96.351 - 9.371 \times 10^{-4} t_{70} \quad (3)$$

where t_{70} is the time under a load of 70% ABL (in h) and R is the retained strength (% ABL).

But for Technora, the reduction in retained strength is much more rapid (as a fraction of its much longer stress rupture lifetime) and it is impossible to fit a curve on the linear time scale. The best fit for retained strength for Technora after time t_{65} h at 65% ABL, on a logarithmic time scale is:

$$R = 99.530 - 0.908 \log(t_{65}) - 0.525(\log(t_{65}))^2 \quad (4)$$

The difference between Kevlar 49 and Technora is less obvious when plotted on log time scales, but dramatic when plotted against linear time, which may be of more relevance to engineers seeking to design with these materials. Plotting on a log time scale gives undue emphasis to short time scales, whereas practicing engineers are more concerned with long-term behavior. Despite the very small number of tests described here, it is believed that the retained strength of Kevlar reduces more slowly than the retained strength of Technora. Clearly, however, an extended study of this phenomenon would be justified.

There is no room here to discuss the likely internal mechanisms that relate to the creep-rupture and strength retention of aramid fibers, but an extensive analysis, using an extension of Northolt's models, is given elsewhere.[23]

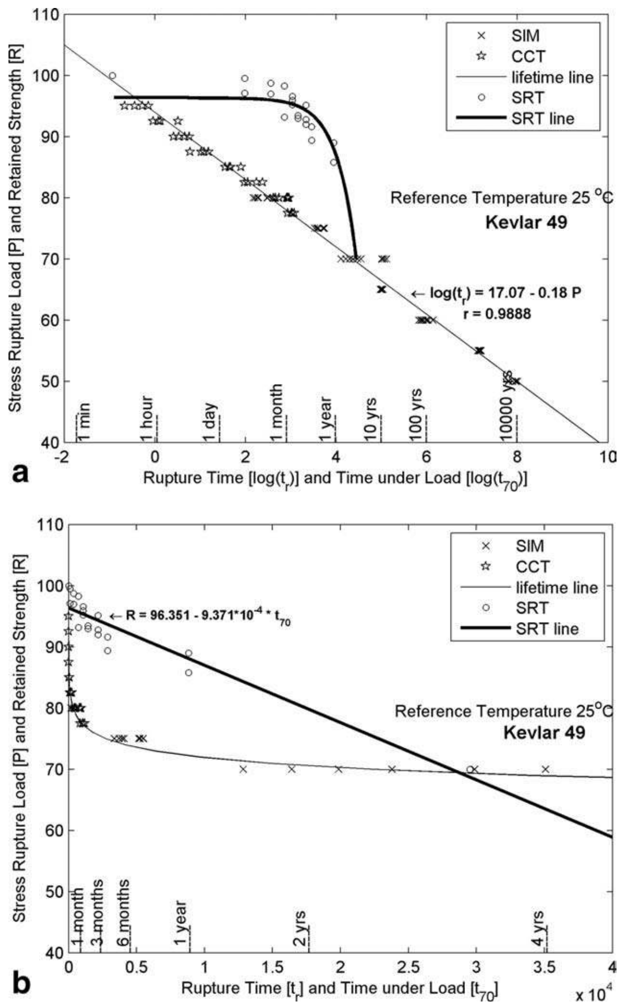

Figure 18 (a) Creep-rupture and retained strength under constant loading using log time scale for Kevlar 49. (b) Creep-rupture and retained strength under constant loading.

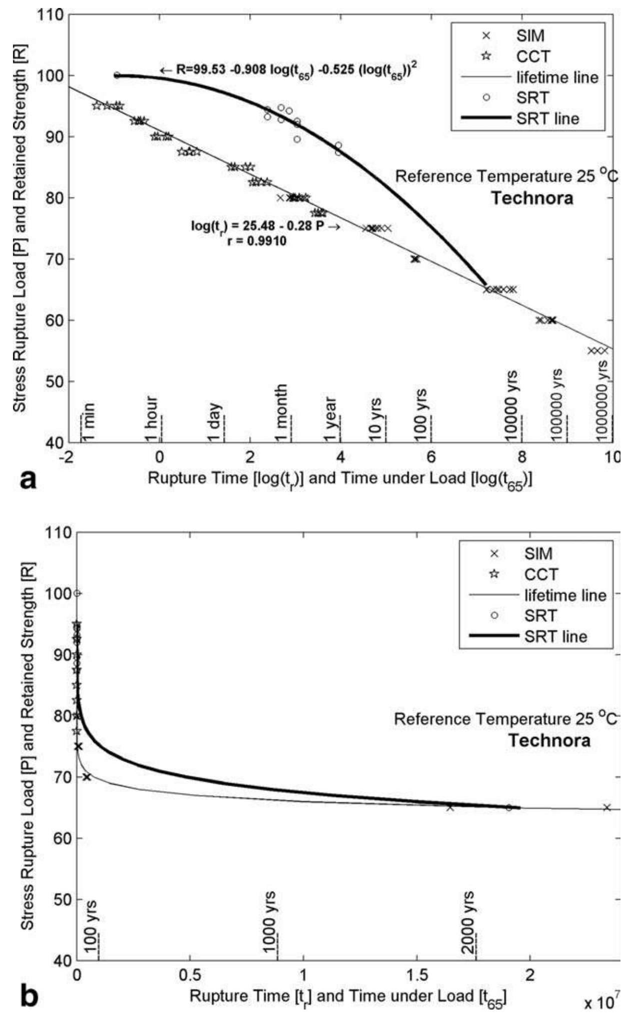

Figure 19 (a) Creep-rupture and retained strength under constant loading using a log time scale for Technora. (b) Creep-rupture and retained strength under constant loading using linear time scale for Technora

CONCLUSIONS

CCT were carried out successfully on Kevlar 49 and Technora yarns under constant temperature (25°C) and humidity (50% RH). The tests covered a wide stress spectrum (10–70% ABL) and lasted up to 1 year.

Their creep and viscoelastic behavior has been investigated and has been found that using a logarithmic time scale the creep curves are practically straight. Also, for the stress range 40–70% ABL both materials are linearly viscoelastic at every elapsed time. For stresses lower than 40% ABL, both materials exhibit nonlinear creep behavior.

The retained strengths due to creep for Kevlar 49 and Technora have been determined. The results show much larger reductions of retained strength for Technora than for Kevlar.

As far as can be ascertained, no creep data for such a long period of time has ever been reported in the past for Kevlar 49 and Technora or for any other aramid fiber. Considering the fact that the use of those materials in various structural applications requires knowledge of the long-term creep behavior, these set of data are very valuable for making firm conclusions about the long-term behavior of aramid fibers.

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