FRPRCS-6, Singapore, 8–10 July 2003
Edited by Kiang Hwee Tan

ACCELERATED TECHNIQUES TO PREDICT THE STRESS-RUPTURE BEHAVIOUR OF ARAMID FIBRES

K. G. N. C. ALWIS AND C. J. BURGOYNE

Department of Engineering, University of Cambridge
Trumpington Street, CB2 1PZ, U.K.

To obtain the stress-rupture data at low stress levels, accelerated testing has been suggested using either the time temperature superposition principle or the stepped isothermal method. These techniques will be applied to Kevlar-49 yarns. The important aspects in obtaining smooth master curves and the validity, both of the techniques and the resulting curves, will also be discussed.

INTRODUCTION

Many models have been suggested over the past decades to predict the long-term stress-rupture behaviour of aramid fibres but they were based on data obtained at high stress levels; extrapolation techniques have been used to predict the behaviour at low stress levels[1,2]. Thus, the validity of these methods is an open issue.

As an alternative, two accelerated testing methods have been suggested to predict the stress-rupture behaviour at low stress levels: the time temperature superposition principle and the stepped isothermal method. These methods offer many advantages when compared to conventional creep tests as testing requires shorter time scales to obtain long-term data.

DESCRIPTION OF THE ACCELERATED METHODS

Time Temperature Superposition Principle (TTSP)

It is assumed that raising the temperature will increase the creep rate but not alter the mechanism. Several individual creep tests are performed at different temperature levels, to obtain strain versus logarithmic time curves. These curves can then be time shifted, parallel to the logarithmic time axis, by an amount a_t to give a single reference curve, on which all the separate test results are superposed. This master curve applies for a certain temperature and a fixed stress level. A comprehensive literature review on early development of the time-temperature superposition principle can be found elsewhere[3] and there have been many applications[4,5].

Materials and experimental set up

In the sample tests described here, Kevlar-49 yarns were used. The average breaking strength load (ABL) of the yarns was 445 N, obtained from 12 short-term tests. The cross sectional area of the yarn was 0.1685×10^{-6} m^2.

The tensile tests were carried out in a conventional testing machine, using round bar clamps that have also been used for long-term dead-weight testing of yarns. The load was applied by moving the cross-head of the machine at a specific rate; the cross-head movement and the load level were recorded.

One of the difficult tasks is to determine the absolute zero of the stress-strain curve, due to initial slack and slippage of the yarn around the jaws. It is essential to know accurately the strain of the specimen just after the initial loading in order to compare the creep curves at different temperatures. A small error of this value would result in displacing the creep curves on the creep strain axis which then makes it impossible to obtain valid, smooth master curves only by making time shifts.

The testing set-up is shown in Figure 1. The oven is set up within the test machine, with the two clamps mounted on extension pieces so that the complete test specimen lies inside the oven. Figure 2 shows accurate stress-strain curves, determined at different temperatures. This figure was used to determine the initial strains for a given stress level at different temperatures. For example, points at which the line AB crosses the stress-strain curves are the initial strain values at 70% ABL. This process is described in detail elsewhere[6].

A series of creep tests were carried out at 70% ABL on Kevlar-49 at different temperatures (25, 40, 60, 80, 100 °C). The initial loading rate was 5 mm/min and the specimen length was 350 mm (centre to centre distance of the jaws). In each test, load was applied only after the temperature had reached the desired value. Thus, by adjusting the initial strains for each test as described above, only time shifts were needed to obtain the master curve.

Results and discussion

Figure 3 shows the raw data of Kevlar-49 specimens at different temperatures. Initial strains of the creep curves just after loading were adjusted according to Figure 2.

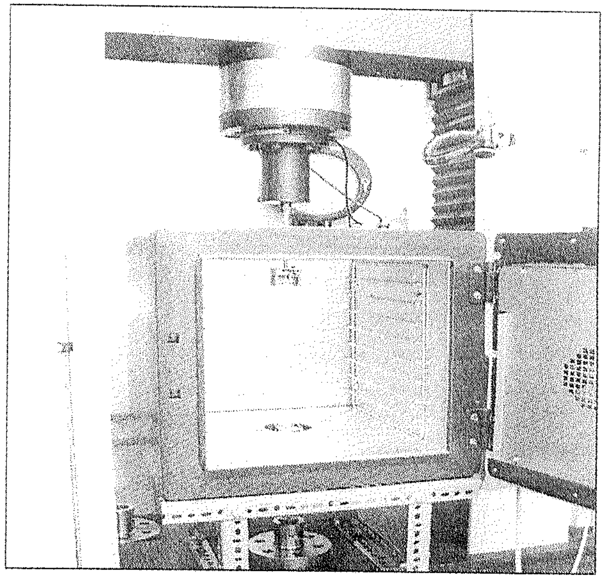

Figure1. Experimental set up for Tensile, TTSP and SIM tests

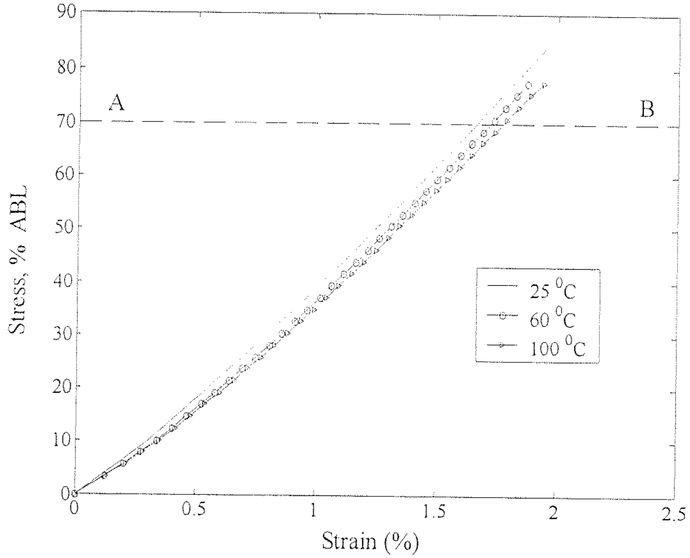

Figure 2. Stress vs. Strain curves at different temperatures[6]

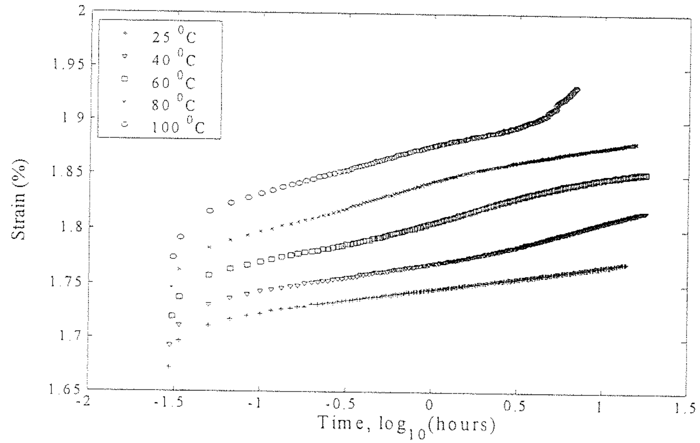

Figure 3. Creep curves at different temperatures

All creep curves (after one hour) were shifted to a reference curve as described earlier until they generate a sufficiently smooth curve. Initially, a graphical method was used to find approximate shift factors, which were then varied in an iterative manner to produce a smooth master curve (Figure 4).

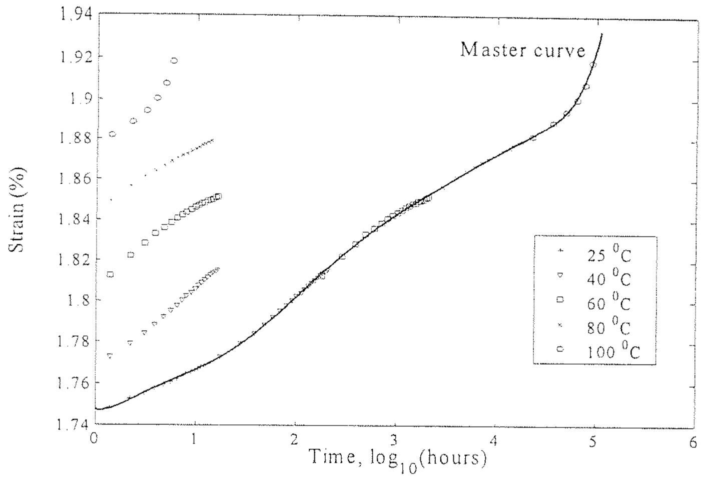

Figure 4. Master curve at 25 ^{0}C and 70% ABL

One of the problems was to decide how the creep response of Kevlar-49 yarns should be parameterised. In past models, the creep response of Kevlar-49 was plotted against the $\log_{10}$ (time) and linear variations were predicted[2]. Alternatively, a power low variation was also used[7]. Tamuzs[8] has done similar testing on Kevlar assuming a series of Kelvin viscoelasticity models to predict the creep behaviour. However, his data can also be fitted with a polynomial of order three. The problem is to select the correct degree of polynomial to describe the data. A higher degree polynomial will give a better fit but there is risk of over-fitting the variables. There are many statistical checks available to decide the appropriate degree of polynomial[9]. In this analysis, a 6th order polynomial was used to describe the creep data of the master curve.

A series of conventional creep tests has also been performed to check the validity of this method. These tests have been carried out in a controlled temperature (25 ^{0}C) and a specified humidity (65% RH). These are the two nominal parameters of the master curve. Figure 5 shows the conventional creep curve plotted with the master curve. The initial part of the conventional curve clearly follows the master curve.

The double curvature of the master curve over $\log_{10}$ (hours) = 2 to 3 of Figure 5 is notable. This may be attributed to re-arrangement of the internal fibers and further microscopic investigations are necessary. However, the reverse curvature of the master curve might imply that the mechanism had changed, which would invalidate the model. To check this, all shift factors were plotted on an Arrhenius plot which gave a straight line. This implies that there is no change in the underlying process, despite the reversal of the master curve. The creep activation energy was found to be 116.3 kJ/mole (27.78 kcal/mole).

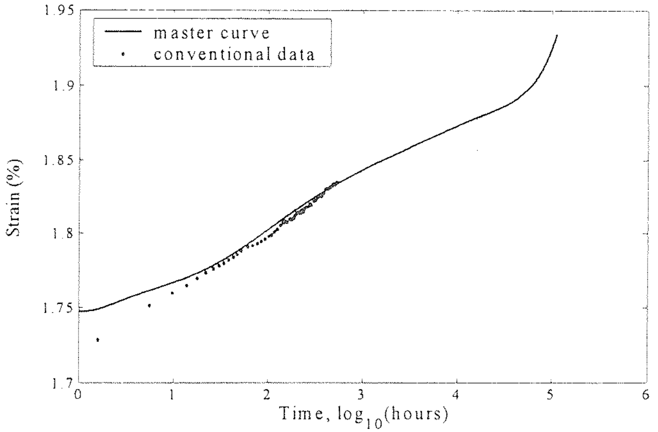

Figure 5. Master curve at 25 ^{0}C and 70% ABL with conventional creep data

Stepped Isothermal Method (SIM)

This approach was first applied to polyester yarns to predict the stress rupture behaviour at moderate tensile loads[10]. The results appeared to be similar to the results obtained from the conventional TTSP tests. In a SIM test, a single specimen is tested at various temperature levels under a constant load, whereas in TTSP testing different specimens are tested at each temperature level. SIM testing thus lends itself to automated testing once the specimen has been loaded into the machine. The SIM procedure can be summarised as:

(a) The test method is similar to that for TTSP. A single specimen is used and the temperature is increased in a series of well-defined steps.
(b) Individual strain versus time curve segments corresponding to different temperatures are shifted in the strain direction to account for thermal contraction/expansion,
(c) Re-scaling in the linear time direction is carried out to account for the thermal history of the specimen,
(d) All curves are shifted parallel to the logarithmic time axis to obtain a reference curve as described in TTSP.

The additional steps needed for SIM interpretation are described below.

Adjustment of strain

Figure 6 shows a schematic picture of a temperature step. The temperature is raised from T_1 to T_2 over the time, t_c. Point B represents the creep strain just after the temperature step; B' is the creep strain that would have been observed due to thermal contraction (aramid fibres have a negative coefficient of thermal expansion). However, the final creep strain, B is observed due to continuing creep over time, t_c (BB'). The adjusted strain just after the temperature step ($\overline{B}$) can be found:-

(a) by adding the thermal contraction, so $\overline{B} = B + B'B''$, or

(b) by adding the creep over t_c, so $\overline{B} = B'' + B'B$

To calculate the distance $B'B''$, an accurate value of the coefficient of thermal expansion is needed, but in the literature different values are stated, so method (a) is not reliable.

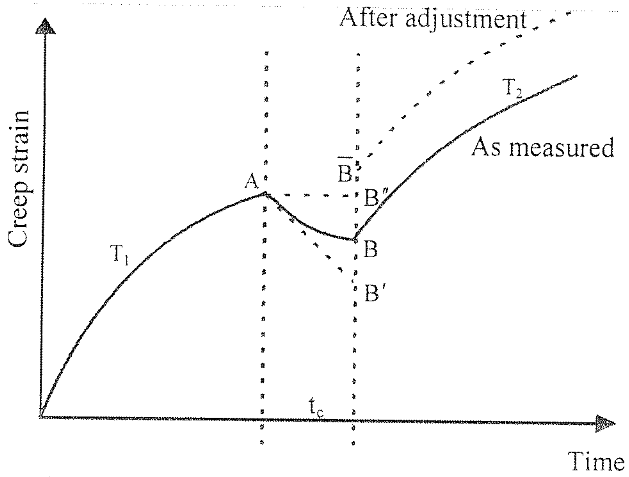

Figure 6. Change of creep behaviour at a temperature step

In contrast, Method (b) can be performed using measured values. Changes of the creep rate over time t_c can be found by conducting separate creep tests from temperature T_1 to a variety of different temperatures. This allows the variation of creep rate with temperature to be measured; the creep over time, t_c (BB') can then be found by integration. A similar procedure has to be applied for each temperature step.

Rescaling procedure

One of the main differences with the SIM approach is that the history of the specimen at different temperatures is not as same as in TTSP. In TTSP a specimen is subjected to a certain temperature level starting from the room temperature whereas in SIM the specimen has a temperature history. Figure 7 shows the strain response for two temperature steps. The curve $OABC$ is the measured response of the SIM specimen through the first two temperature steps. $OA\overline{B}\overline{C}$ is the response after making the strain adjustment. PQ is the response of a TTSP test carried out at the higher temperature T_2. It is now necessary to determine the time t' which represents the notional starting time for a TTSP specimen that would have the same response as the SIM specimen at the higher temperature. The value $t'' - t'$ is assumed to be the time needed for a specimen which had always been at T_2 to arrive at the creep state at time t''. It should be equal to

t^* from the TTSP curve. The selection of t' for each temperature step has a great influence when obtaining smooth master curves.

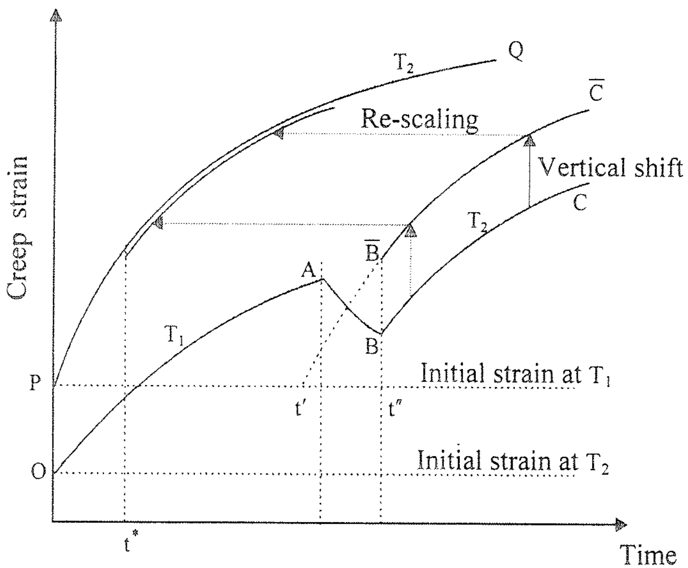

Figure 7. Re-scaling procedure for SIM

A numerical procedure has been developed to select the rescaling time t' (which is applied in linear time) and the time shifting parameter a_t (which is applied in logarithmic time), to produce a smooth master curve. Figure 8 shows three master curves, one obtained from a set of TTSP tests, and the other two obtained from SIM tests with different combinations of temperature steps. If the method has any validity, these master curves should be similar, to within the normal limits of variation between different fibres. The results in Figure 8 show that the method is promising.

It is now possible to investigate stress-rupture behaviour. Each of the master curves on Figure 8 ends with the failure of a yarn. If the master curves are truly representative of the creep curves of the yarn, then it is reasonable to suppose that the times to failure on the figure represent the times to failure that would have been observed in long-term tests.

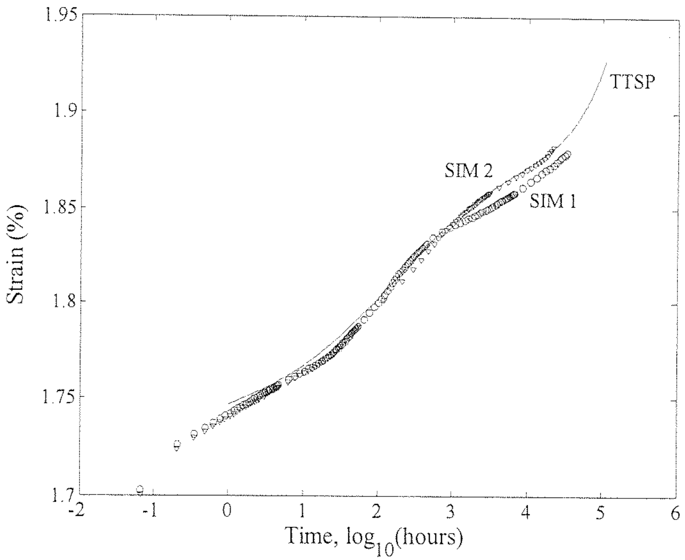

Figure 8. Master curves from TTSP and SIM

CONCLUSION

TTSP can be successfully applied to predict the long-term creep behaviour of aramid. The SIM method can be used to mimic the behaviour of TTSP tests. Both methods can be used to predict the rupture times of yarns at low stress levels.

The fundamental question remains whether the master curve obtained by the two methods described here, which appear to be self-consistent and repeatable, truly represents the behaviour of fibres tested over very long time-scales at ambient temperature. If this could be proved, then the SIM method has great potential for accumulating data very quickly.

REFERENCES

1. Guimaraes, G.B., "Parallel-lay aramid ropes for use in structural engineering", PhD Thesis submitted to the University of London, 1988.

2. Ericksen, R.H., "Creep of Kevlar 49 fibres", *Proc. of 2nd Symp. on failure modes in composites*. Metall. Soc. of AIME, New York, 1984 302 pp.
3. Ferry, J.D., "Viscoelastic properties of polymers", John Wiley and Sons, Inc., 1970.
4. Povolo, F. and Hermida, E.B. "Analysis of the master curve for the viscoelastic behaviour of polymers", *Mechanics of Materials*, No. 12, 1991, pp. 35-46.
5. Brinson, L.C. and Gates, T.S., "Effects of physical aging on long term creep of polymers and polymer matrix composites", *Int. J. Solids and Structures*, Vol. 32, No. 6/7, 1995, pp. 827-846.
6. Alwis, K.G.N.C, PhD thesis in preparation, University of Cambridge.
7. Walton, R.E. and Majumdar, A.J., "Creep of Kevlar 49 fibre and a Kevlar 49-cement composite", *Journal of Materials Science*, Vol. 18, 1983, pp. 2939-2946.
8. Tamuzs, V., Maksimovs, R. and Modniks, J., "Long-term creep of hybrid FRP bars", 5th *International Symposium on FRP Reinforced Concrete Structures (FRPRCS-5)*, Cambridge, July 8-10, 2001, Vol. 1, pp. 527–535.
9. Draper, N.R., and Smith, H., "Applied regression analysis", John Wiley and Sons, Inc., 1966.
10. Thornton, J.S., Allen, S.R., Thomas, R.W. and Sandri, D., "The stepped isothermal method for TTS and its application to creep data on polyester yarn", *Sixth International Conference on Geosynthetics*, Atlanta, USA, 1988.