Stepped Isothermal Method for Creep Rupture Studies of Aramid Fibres

by K.G.N.C. Alwis and C.J. Burgoyne

Synopsis: Aramid fibres have been used in rope construction and for prestressing tendons, but when subjected to a constant static load the fibres creep with time and may rupture, leading to a catastrophic failure of the rope. To understand this behaviour many life-time models have been suggested but they suffer from the lack of long term creep rupture data to make firm conclusions on rupture times and load levels. Such data is expensive to obtain using conventional creep testing as it takes a long time before failure of a specimen. To overcome this problem, and to obtain the creep-rupture data at low stress levels within a reasonably short time scale (hours), accelerated testing methods, the Stepped Isothermal Method (SIM) and Time Temperature Superposition (TTSP), have been investigated. In SIM testing a single yarn specimen is tested at a specific stress level under a series of increasing temperature steps from which a single response curve, known as the master curve, is obtained which predicts the long-term behaviour. Some manipulation of the data is required, but the technique has many advantages over the TTSP and conventional creep testing and it can be automated to obtain the long-term creep-rupture data points relatively easily.

Keywords: accelerated testing; creep-rupture; master curve; stepped isothermal method (SIM)

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INTRODUCTION

If high-strength fibres, such as aramids, are to find practical application in structural engineering, it is most likely to be as non-corrodable external (or unbonded) prestressing tendons in concrete. In such applications, where the applied stress varies very little, the governing factor is not going to be the short-term strength, or modulus, but the long-term creep-rupture strength.

It takes a long time however, using conventional creep tests, to obtain creep-rupture data for aramid fibres at the low stress levels likely to be used in practical applications. As an alternative, two accelerated testing methods have been suggested to predict the creep-rupture behaviour at low stress levels: the time temperature superposition principle (TTSP) and the stepped isothermal method (SIM). These methods offer many advantages when compared to conventional creep tests as testing requires shorter time scales to obtain long-term data.

In 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 $log\ (a_t)$ 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. This technique is not described in the paper but a detailed description can be found in elsewhere[1]. A comprehensive literature review on early development of the time-temperature superposition principle can also be found elsewhere[2] and there have been many applications[3,4]. In this paper, however, the creep rupture data obtained from TTSP method is used to compare with the results obtained from SIM.

Thornton et al.[5] first applied the SIM to predict the long-term creep behaviour of geogrids in soil reinforcement applications; for this application there is virtually no conventional creep data and test data derived from SIM has been accepted as the basis of design rules. The principle of the SIM is that a single element (in this case a yarn) is placed in a testing machine and loaded by a chosen force. The temperature is then raised, typically by a few °C, and kept constant for a fixed period of time, typically a few hours. The sequence is then repeated at a slightly higher temperature, on the same sample. Some manipulation of the data is required in order to compensate for the temperature steps. The SIM can be considered as a special case of the TTSP, a detailed description of which is given elsewhere[1,6]. In SIM tests, a single specimen is tested at a sequence of temperature levels under a constant load, whereas in TTSP testing different specimens are tested at each temperature level. SIM is very promising when compared to TTSP and conventional creep tests since a yarn can be tested until it fails in a much shorter time; this depends on the temperature and time steps adopted.

Three different adjustments are needed for each SIM test to produce a single master creep curve; the creep-rupture prediction comes from the end of the master curve when the specimen fails under a specific load and temperature (Figure 1). The ***vertical shift*** allows for the strains caused by the change in temperature, taking account of the creep that occurs while the temperature change is taking place. ***Rescaling*** is needed to allow for the previous history of the specimen: when the temperature changes some allowance must be made for the fact that some creep has already taken place under the previous time steps, unlike TTSP when each test is separate. This adjustment takes the form of a shift in the time direction when plotted against a *linear* time scale. The ***horizontal shift*** takes the form of a shift on a creep strain vs. *log* (time) plot and is similar to the technique used in TTSP to allow comparison of tests at different temperatures. Each of these adjustments will be described in more detail below.

RESEARCH SIGNIFICANCE

The paper presents a method that can be used to obtain creep-rupture test data for fibres in a short time-scale from which predictions can be made for the behaviour of the materials over very long time-scales in practical applications. This paper does not, of itself, provide answers to the many questions which remain about the behaviour of these fibres, but it does give a technique which can be used to address them.

MATERIALS AND EXPERIMENTAL SET-UP

In the sample tests described here, Kevlar-49 yarns were used. The average breaking load (ABL) of the yarns was 445 N, obtained from 12 short-term tests. All test results described below will be reported relative to the ABL, since it is known that size effects can be taken into account by relating all stresses to the short-term breaking load[7]. 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. The testing set-up is shown in Figure 2; 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.

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.

An extensive study was thus first carried out, using spring-steel hoops fitted with high-temperature strain gauges, to determine the jaw effect. This was carried out with yarns of different length, and with the oven set at different temperatures. This procedure allowed the SIM tests to be carried out using machine extension alone, since the clamping action on the spring-steel gauges might affect the stress-rupture lifetime of the yarns.

By separating the jaw effect from the yarn extension, it is possible to determine accurate stress-strain curves for the yarns, at different temperatures, as shown in Figure 3. These graphs were 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[8].

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; by adjusting the initial strains for each test as described above, only time and vertical shifts were needed to obtain the master curve.

Testing procedure

A series of SIM tests were carried out at 70% ABL on Kevlar-49 at different steps of temperature over different time steps. All tests started at 25 °C as it was easy to control this temperature by heating only. The testing machine was kept in a temperature-controlled room where the temperature was maintained at 21 °C. It was not possible to carry out any tests below this value since the oven had no cooling facility.

Load was applied only after the temperature had reached 25 °C, so no initial correction for temperature was needed. Table 1 shows the temperature sequences used for the tests reported here; different sequences were used since, if the method is to be valid, similar master curves must be obtained no matter what temperature steps are used.

Each yarn was tested to failure; the failure point could be observed from the load reading of the testing machine and it was not necessary to open the oven for investigation. Two tests were carried out at each test number; to distinguish them the following identification was used:

- SIM70-01-01
- SIM70-01-02

'70' denotes the load level, the succeeding number '01' denotes the test number and the last number denotes the repetition of the test. A similar testing procedure was used to test the yarns at 50% ABL but at different time and temperature steps; space does not allow that data to be included here.

ADUSTMENT OF STRAIN FOR CHANGE IN TEMPERATURE-VERTICAL SHIFT

Figure 4 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, noting that 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.

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. This means that many subsidiary tests have to be performed, but avoids reliance on uncertain published data.

RESCALING PROCEDURE

One of the main differences with the SIM approach is that the history of the specimen at different temperatures is not the same as in TTSP. In TTSP a specimen is subjected to a certain temperature level starting from room temperature whereas in SIM the specimen already has a strain history caused by extensions that took place at previous temperature steps.

Figure 5 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 vertical 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' that 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 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. A graphical method is used to obtain an initial estimate of the time t' by extending the $\overline{C}\overline{B}$ curve as smoothly as possible on to the horizontal line that passes through P, which is then refined numerically.

THE HORIZONTAL SHIFT

This step is similar to the shifting procedure as used for TTSP[1]. Once the vertical and rescaling shifts have been carried out the SIM data represent a set of creep curves, as would have been obtained using the TTSP method. The adjustment therefore takes the form of a horizontal shift on a creep strain vs. *log* (time) plot. In the SIM approach it is necessary to perform the rescaling and horizontal shifts together using a numerical procedure. Once the possible ranges of the rescaling and horizontal shifts have been identified using a graphical method, an automated numerical procedure is used by fitting a polynomial through the overlap region and adjusting the shifting and scaling parameters to minimise the lack-of-fit of the two overlapping curves. The same technique is then carried out at each temperature step which results in a single, smooth creep curve (the master curve) for a known load at a specified temperature. This master curve, examples of which are shown in Figures 6 and 7, represents the best estimate of the extension against time at the specified temperature, under the given load. If the specimen was allowed to creep until failure, the end point of the master curve gives a data point for creep-rupture.

RESULTS AND DISCUSSION

A series of conventional creep tests have been performed to check the validity of this method. These tests have been carried out in a controlled temperature (25 °C) and humidity (65% RH) environment. For comparison, SIM70-01-01 data is plotted together with the TTSP data and conventional creep data at 70% ABL (Figure 6). All curves match reasonably closely and SIM seems to be promising since the curves match both in form and position. However, even if the SIM test picks up the basic form of the results, a question remains about its repeatability. All SIM curves at 70% ABL are plotted in Figure 7; it is apparent that all curves follow the same shape which indicates its repeatability, even though different temperature steps were used for each test.

The initial part of Figure 6 shows that the conventional curve clearly follows the master curve. There is, however, speculation about the reverse curvature of the master curves between 100 to 10,000 hours. The same behaviour was observed for the master curves generated from TTSP and also for SIM tests carried out at 50% ABL[8]. The behaviour may be attributed to re-arrangement of the internal fibres and is independent of the type of the accelerating method. This reverse curvature of the creep response has not been described in the literature and this may be the first time it has been observed. It is not possible at this stage fully to understand this response since only a limited amount of testing has been carried out. Further investigation should be carried out with a variety of tests at different stress levels, different time steps and different temperature steps to come to a firm conclusion.

It is also significant to note that the horizontal shift factors needed to produce the master curves turn out to vary inversely with the absolute temperature[8]. This indicates that creep can be regarded as an Arrhenius process and is consistent with observations elsewhere[6].

The availability of SIM means that it is now possible to investigate creep-rupture behaviour in much more detail. Each of the master curves on Figure 7 ends with failure of a yarn. For comparison these failure times are plotted in Figure 8 along with the best statistical life prediction based on Kevlar rope data[8]. It is apparent that the failure times of some of the SIM data at 70% ABL lie within the confidence limits of the model, but there is more spread of the rupture times than predicted by the statistical model; the rupture times predicted by SIM are considerably longer. More testing is needed at low stress levels before firm conclusions can be reached. The results presented here do not, of themselves, answer such questions as the effect of varying loads, varying temperature or problems associated with cumulative damage. But these results do show that SIM testing provides a tool which can be used to obtain some of the necessary data, and also to provide a prediction of future behaviour against which other theories can be tested.

CONCLUSION

SIM can be readily applied to generate long-term creep-rupture data of aramid yarns and can be used to mimic the behaviour of TTSP tests. The SIM technique has many advantages over conventional TTSP. Both the test procedures and the data reduction can be automated, and a single specimen can be tested at each stress level for the entire thermal history within a reasonably short time scale; the effects due to the variability of yarns can thus be minimised.

SIM results show repeatability but there was some variation of the rupture times which may be attributed to the variability of the yarns. The technique seems to be promising and can be recommended as a basis to generate more rupture data at different stress levels.

REFERENCES

[1] Alwis, K.G.N.C and Burgoyne, C.J, 2003, “Accelerated testing to predict the stress-rupture behaviour of aramid fibres”, *Fibre reinforced plastics for reinforced concrete structures (FRPRCS-6)*, Edited by Kiang Hwee TAN, Singapore, 2003, pp. 111-120.

[2] Ferry, J.D., 1970, "Viscoelastic properties of polymers", John Wiley and Sons, Inc.

[3] Povolo, F. and Hermida, E.B., 1991, "Analysis of the master curve for the viscoelastic behaviour of polymers", *Mechanics of Materials*, No. 12, pp. 35-46.

[4] Brinson, L.C. and Gates, T.S., 1995, "Effects of physical aging on long term creep of polymers and polymer matrix composites", *Int. J. Solids and Structures*, Vol. 32, No. 6/7, pp. 827-846.

[5] Thornton, J.S., Allen, S.R., Thomas, R.W. and Sandri, D., 1988, "The stepped isothermal method for TTS and its application to creep data on polyester yarn", *Sixth International Conference on Geosynthetics*, Atlanta, USA.

[6] Tamuzs, V., Maksimovs, R. and Modniks, J., 2001, July 8-10, "Long-term creep of hybrid FRP bars", 5th *International Symposium on FRP Reinforced Concrete Structures (FRPRCS-5)*, Cambridge, Vol. 1, pp. 527–535.

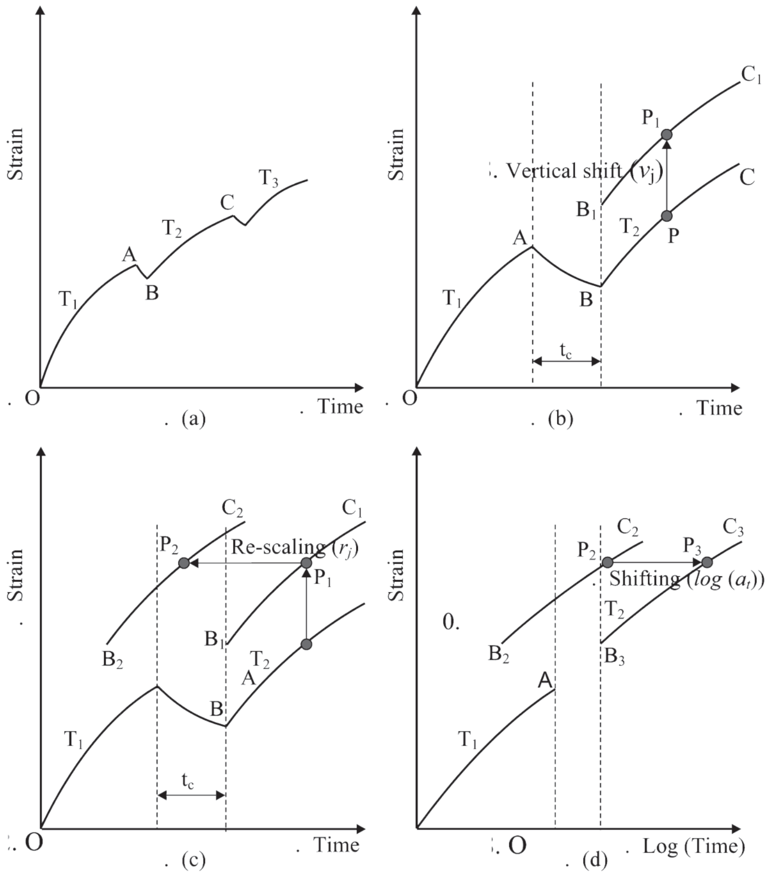
[7] Amaniampong, G. "Variability and viscoelasticity of parallel-lay ropes", Thesis submitted to the University of Cambridge, 1992.

[8] Alwis, K.G.N.C, "Accelerated testing for long-term stress-rupture behaviour of aramid fibres" Thesis submitted to the University of Cambridge, 2003.

Table 1 – SIM tests at different temperature steps (^{0}C) at 70% ABL

Test No.	No. of tests	Time duration for each temperature step				
		5hrs	5hrs	5hrs	5hrs	5hrs
SIM70-01-01/02	2	25	40	60	80	100*
SIM70-02-01/02	2	25	40	80	100*	-
SIM70-03-01/02	2	25	40	60	100*	-
SIM70-04-01/02	2	25	40	60	80	120*
SIM70-05-01/02	2	25	40	80	120*	-
SIM70-06-01/02	2	25	60	80	100*	-
SIM70-07-01/02	2	25	60	100*	-	-
SIM70-08-01/02	2	25	60	80	120*	-

* Final step extended until failure



(a) Strain vs. time
(b) Adjustment in strain direction
(c) Rescaling
(d) Shifting

Figure 1 – SIM procedure in schematic diagrams

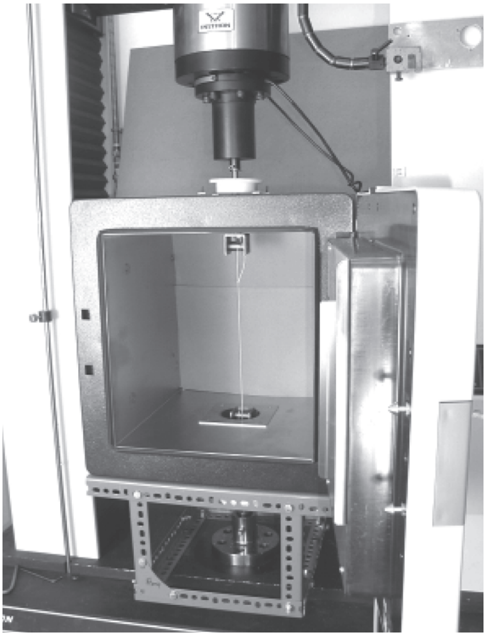


Figure 2 – Experimental set-up for tensile, TTSP and SIM test

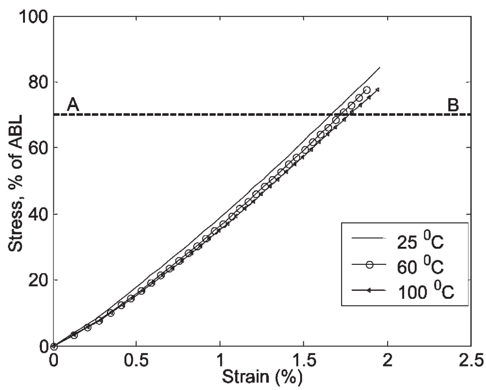


Figure 3 – Stress vs. strain curves at different temperature

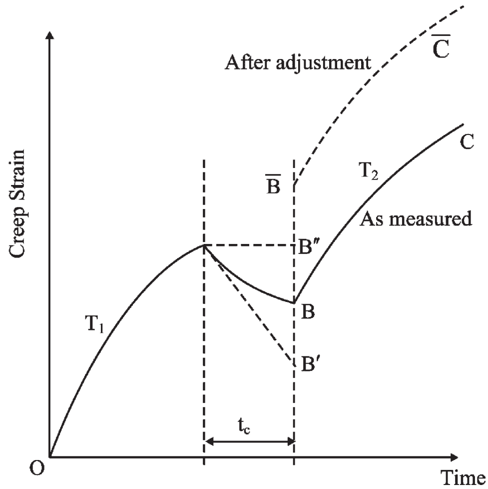


Figure 4 – Change of creep behaviour at a temperature step

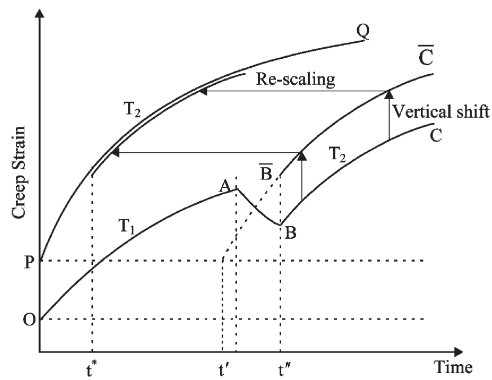


Figure 5 – Rescaling procedure for SIM

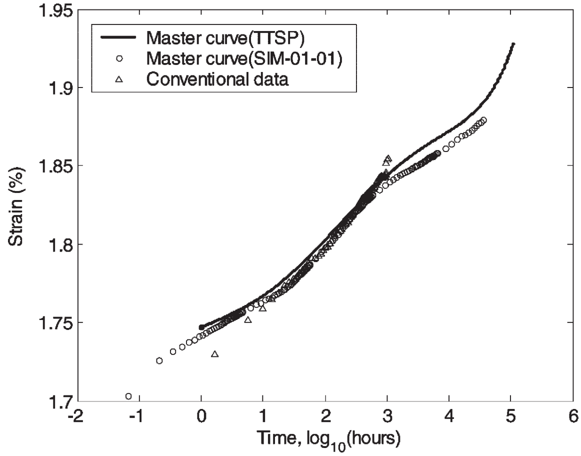


Figure 6 – Master curves with conventional creep data at 70% ABL

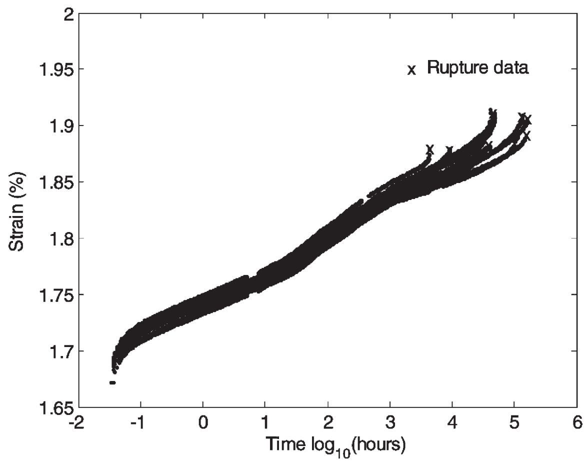


Figure 7 – All SIM master curves at 70% ABL

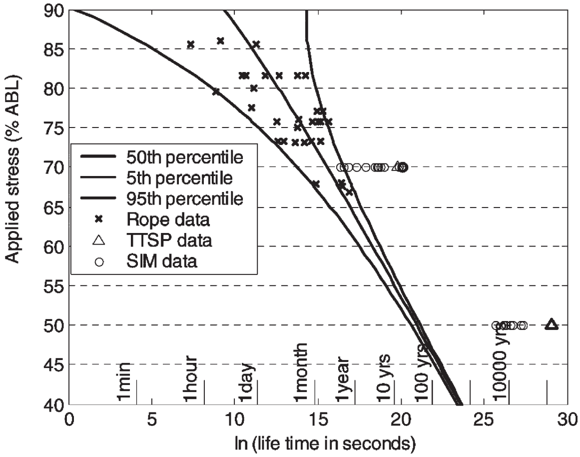


Figure 8 – Comparison of stress rupture data at 50 and 70% ABL