STEPPED ISOSTRESS METHOD FOR ARAMID FIBERS

Ioannis P. GIANNOPOULOS [1] Chris J. BURGOYNE [2]

[1] PhD student, Department of Engineering, University of Cambridge, UK
[2] Reader in Concrete Structures, Department of Engineering, University of Cambridge, UK

Keywords: kevlar 49, technora, stepped isostress method, stress-rupture, accelerated testing, activation volume.

1 INTRODUCTION

Aramid fibres are widely used in many structural engineering applications; they are used as tendons in prestressed concrete, as stay cables in bridges and as ropes in marine industry due to their good tensile properties, low weight and lack of corrosion. Therefore, their time dependent mechanical behaviour and especially their long-term performance are crucial for structural designers. Most polymers, like aramids, exhibit time-dependent mechanical behaviour, usually referred to as viscoelasticity. Viscoelasticity can be influenced by many factors such as temperature, physical aging, damage, pressure, solvent concentration, strain or stress. Among them, temperature and stress are the two most important factors for load-bearing polymeric materials. The well-known Time Temperature Superposition concept (TTS) has been extensively used in the past to predict the long-term stress-rupture behaviour of polymers [1-4].

The stress effect has also received much attention the last years, and the Time Stress Superposition concept (TSS) has been proposed and used to predict the creep behaviour of various polymeric materials. Various researchers [5-7] have performed creep tests at various stress levels and at ambient temperature conditions, and have constructed a master curve at reference stress using the Time Stress Superposition Principle (TSSP). By taking into account the combined effect of temperature and stress on the creep of viscoelastic materials, other researchers [8,9] have tested different specimens at various temperatures and stress levels. First, the time-temperature principle is applied to produce master curves at various stress levels at a selected reference temperature. Then, the time-stress principle is applied on the obtained master curves to get the final master curves at a reference stress and temperature level.

Based on the methods described above a different accelerated method, called the Stepped Isostress Method (SSM), is introduced in the present paper to predict the long-term creep behaviour of Kevlar 49 and Technora. This method involves loading a single specimen, instead of the many specimens required in TSSP. This single specimen is subjected to a series of timed isostress exposures at elevated stress levels in a stepped fashion under constant temperature. At each stress step a creep curve (strain vs. time) is obtained; these can be adjusted to compensate for the different stress levels and a creep master curve at a reference stress level is produced. A stress – rupture point can then be determined as the very last point of each creep master curve.

Four different adjustments are needed for each SSM test to produce a single master creep curve (initial vertical adjustment, vertical shifting, rescaling and horizontal shift). The Boltzmann superposition principle and Eyring equation provide justification for rescaling and horizontal shifting of the creep curves obtained at each isostress exposure in order to produce a creep master curve at a reference stress. These adjustments are described in more detail elsewhere [10].

The use of a single specimen minimises concerns about specimen variability and handling effects; TSSP needs more specimens and more handling. SSM can be automated and takes less time than TSSP, so offers several advantages.

2 MATERIALS AND EXPERIMENTAL SET-UP

Kevlar 49 and Technora yarns, available in reel forms, were used for all tests. The cross sectional areas (A) of the yarns, after removing moisture, were found to be 0.175 mm^2 and 0.123 mm^2 respectively. The breaking load (445 N for Kevlar and 349 N for Technora) was determined by testing twenty different specimens for each material. All values obtained are in agreement with the literature [11,12]. Before testing the yarn reels were kept at constant room temperature (25 ^oC) and humidity (50 % relative humidity), placed in a black polyester bag inside a box to protect them from ultra violet light.

Four different types of testing for the yarns were used; tensile tests, using a mechanical strain gauge, were carried out to obtain accurate stress vs. strain curves at different temperature levels;

accelerated creep tests (SIM tests at different stress levels and increasing temperature levels and SSM tests at different stress levels with constant temperature and increasing stress levels); conventional creep tests (CCT) at different stress levels under constant temperature and humidity.

Tensile, SIM and SSM tests were conducted using the same experimental set-up (Fig. 1), while CCT were conducted using a different experimental set-up (Fig. 2). Details can be found elsewhere [4,10].

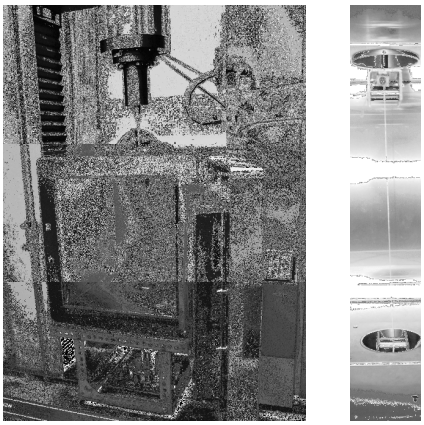

Fig. 1 Experimental set-up for tensile, SIM & SSM tests

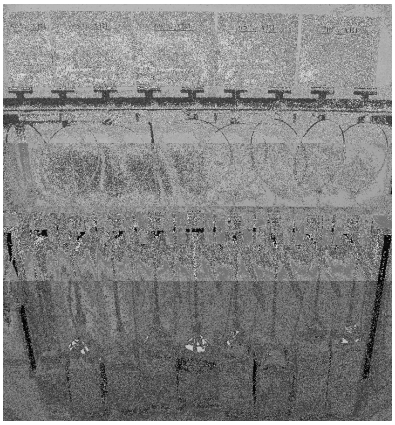

Fig. 2 Experimental set-up for CCT tests

Testing Procedure

SSM tests for Kevlar 49 and Technora yarns at different initial stresses and increasing stress levels were carried out. The yarns were chosen from the same reel as those for the tensile and SIM tests. The nominal length of the specimen (distance between clamped ends) was 350 mm. An initial temperature of 25 ^{o}C (chosen to be slightly above ambient) was reached in all SSM tests before applying load using the Instron machine.

A series of 4-5 stress steps were then applied to the specimen. Each stress step was chosen to last 5 hours, except the last which continued until failure of the specimen occurred. The stress steps were chosen to give failure after about 24 hours so that a daily cycle of tests could be performed.

Four tests were conducted at each load level: 50, 55, 60, 65, 70, 75% of Average Breaking Load (ABL), using two different stress sequences, each repeated once. If the method is valid, similar master curves should be obtained from different stress sequences. Experiments were not conducted below 50% ABL, since Kevlar 49 and Technora show non-linear visco-elastic behaviour below 40% ABL [10,13].

SIM and CCT tests for Kevlar 49 and Technora yarns were also carried out at different stress levels [4,10]. The resulting creep strain vs. time curves at different stress levels are used to be compared with the corresponding curves obtained from SSM tests.

3 RESULTS AND DISCUSSION

Detailed results are presented below for one test on Kevlar 49 followed by a summary of all the results for Kevlar 49 and Technora.The test readings monitored throughout each SSM test were used to produce the following plots: specimen elongation (Δl) vs. time (t), applied load (P) vs. time and temperature (T) vs. time. The load was applied in a step fashion way and temperature was held constant at 25 ^{o}C. The elongation vs. time curve was then converted to a strain vs. time curve (Fig. 3). This was done by using the following relationships:

$$\sigma = P/A$$

$$\varepsilon = (\Delta l - s)/l_{eff} \qquad \text{where } l_{eff} = l_{nom} + l_{jaw}$$

The initial slack s and the jaw effect l_{jaw} have been determined by the method described elsewhere [10] and were found to be 0.42 mm and 140.0 mm respectively for Kevlar 49, and 0.20 mm and 128.0 mm respectively for Technora. The resulting strain vs. time curve at an applied stress level is adjusted up and down to give an initial strain at zero time which is the same as that from the stress vs. strain curves in tensile testing obtained by the mechanical strain gauge.

At each stress step, such as AB from stress level 75 to 77.5% ABL in Fig. 3, an increase of strain from A to B is observed. This increase corresponds to the elastic strain between the two stress levels only. Since the stress step is done almost instantaneously, there is no creep strain from A to B. The

creep curve at stress 80% ABL after the step must be shifted vertically to remove the elastic strain, so that the final master curve is a purely creep curve. This can be done using two methods, which are described elsewhere [10].

Each part of the curve of Fig. 3, corresponding to a different stress level, has to be rescaled by horizontal shifting in order to take into account the stress history of the specimen and to form a creep master curve. In order to obtain a smooth master curve a third order polynomial was fitted to the curves just before and after each stress step; the result is the final smooth master curve (Fig. 4). The very last point of this curve corresponds to the creep–rupture point of the specimen. For the examined test the rupture time is $10^{3.084}$ hours = 50 days = 0.139 years. Details of all applied adjustments mentioned above are given elsewhere [10].

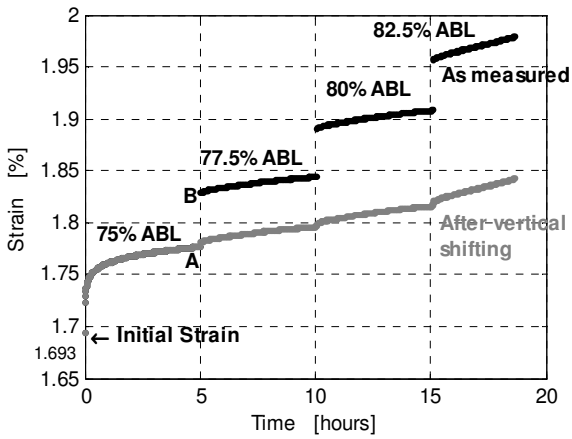

Fig. 3 Strain vs. time curve as measured and after vertical shifting

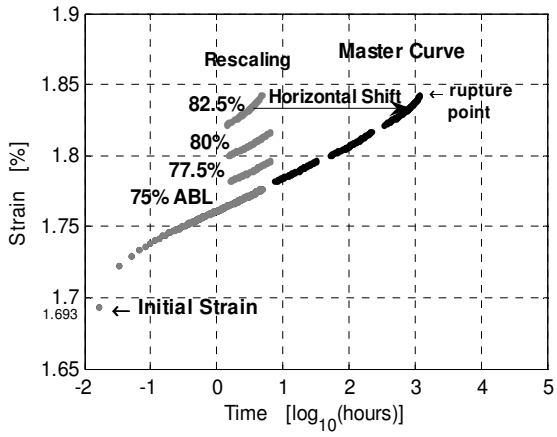

Fig. 4 Individual creep curve after rescaling and master curve after horizontal shifting

The above procedure is followed at all load levels: 50, 55, 60, 65, 70, 75 % ABL. All master curves from all tests are shown together in Fig. 5. Examining the SSM master curves at each load level, which resulted from four tests with different stress sequence, it is noticed that they match both in form and position with some experimental scatter. From all curves it can be seen that creep strain values are linearly increasing with the logarithmic time. A good agreement is observed with the corresponding creep master curves obtained from the well established SIM tests (grey lines).

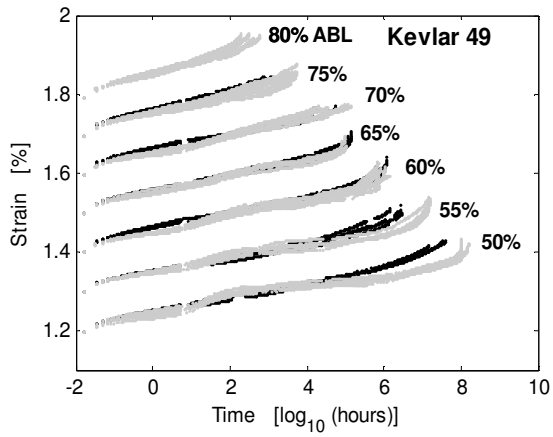

Fig. 5 Master curves from SIM tests (grey) and SSM tests (black) for Kevlar 49

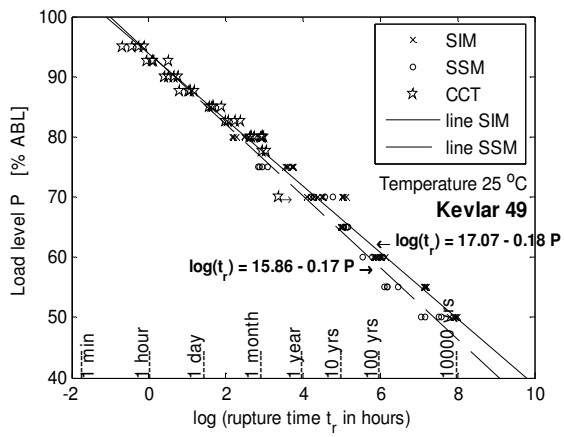

Fig. 6 Rupture times of SIM, SSM and CCT for Kevlar 49 yarns at ref. temp 25 °C

All accelerated SSM tests at various load levels were carried out until failure of the specimen (Fig. 5). The very last point of a master curve corresponds to the rupture time of the specimen at the reference temperature (25 °C). The creep-rupture-time values are plotted at various load levels (Fig 6). It is observed that for load levels between 50 and 77.5% ABL there is a linear increase of the rupture logarithmic time with decreasing applied load, given by equation:

$$\log(t_r) = 15.86 - 0.17\,P \qquad \text{for Kevlar 49}$$

$\log(t_r) = 19.52 - 0.21\ P$ for Technora

The variation of the test data at all load levels about this line is small, indicating the success of the SSM in deriving rupture times which by conventional creep tests would have required months or years. Conventional creep rupture tests (CCT) between 77.5% and 95% ABL and Stepped Isothermal Method (SIM) tests between 50% and 80% ABL for Kevlar 49 and Technora are available [4,10] for comparison purposes with Stepped Isostress Method (SSM) tests. All rupture data points are plotted together at the reference temperature and a good agreement is observed, which proves that the SSM technique is working well.

4 CONCLUSION

Stepped Isostress Method (SSM) tests have been successfully carried out on Kevlar 49 and Technora yarns for a wide range of loads (50 - 75% Average Breaking Load). The test data are used to determine the stress-rupture time of Kevlar 49 and Technora. A linear increase in the logarithmic rupture time with decreasing applied load is shown for the two materials. The two aramid fibres give different results, which may reflect their slightly different chemical structure. The present work is compared together with data obtained from different techniques (SIM and CCT) and a good agreement of the data is observed.

SSM technique is a promising method and seems to be more advantageous when compared with SIM. In SSM testing stress is used instead of heat to provide the energy needed to overcome the barrier to creep movement. There is no need to use an oven to get the elevated temperatures required, which may affect the chemical properties of the materials.

It can be concluded that SSM is a reliable accelerated creep testing technique which can be applied successfully to high-modulus aramid fibres. This allows more certainty about the stress-rupture relationships for different fibres, which will in turn allow more realistic safety factors to be applied when designing engineering applications with these materials.

REFERENCES

[1] Thornton, J. S., S. R. Allen, R.W. Thomas and D. Sandri. "The stepped isothermal method for TTS and its application to creep data on polyester yarn", *Sixth International Conference on Geosynthetics*, Atlanta, USA, 1998.

[2] Zornberg, J. G., R. Brett and W. Justin (2004). "Creep of Geotextiles Using Time–Temperature Superposition Methods", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 11: pp. 1158-1167.

[3] Alwis, K. G. N. C. and C. J. Burgoyne (2008). "Stepped Isothermal Method for Creep Rupture Studies of Aramids", *Journal of Materials Science*, Vol. 43, No. 14: pp. 4789-4800.

[4] Giannopoulos, I.P. and C.J. Burgoyne (2008). "Stepped Isothermal Method (SIM) test results for Aramid Fibres", *5th Conf. on Advanced Composite Materials in Bridges and Structures (ACMBS-V)*, Paper 79, Winnipeg, Canada.

[5] Lai, J. and A. Bakker (1995). "Analysis of the non-linear creep of high-density polyethylene", *Polymer*, Vol. 36, No. 1: pp. 93-99.

[6] Hadid, M., S. Rechak and A. Tati (2004). "Long-term bending creep behaviour prediction of injection molded composite using stress–time correspondence principle", *Materials Science and Engineering*, A 385: pp. 54–58.

[7] Jazouli, S., W. Luo, F. Bremand and T. Vu-Khanha (2006). "Application of Time-Temperature-Stress Superposition Principle to Nonlinear Creep of Poly(methyl methacrylate) ", *Key Engineering Materials*, Vols. 340-341: pp. 1091-1096.

[8] Ma, C.C.M., N.H. Tai, S.H. Wu, S.H. Lin, J.F. Wu and J.M. Lin (1997). "Creep behavior of carbon-fiber-reinforced polyetheretherketone (PEEK)", *Composites,* Part B, 28B: pp. 407-417.

[9] Luo, W., C. Wang (2007). "Application of Time-Temperature-Stress Superposition Principle to Nonlinear Creep of Poly(methyl methacrylate)", *Key Engineering Materials*, Vols. 340-341: pp. 1091-1096.

[10] Giannopoulos, I. P. (2009). "Creep – rupture behaviour of high modulus fibres", University of Cambridge, PhD thesis in preparation.

[11] Du Pont (1991). "Data manual for fibre optics and other cables", E. I. Du Pont de Nemours and Co. (Inc.).

[12] Teijin Ltd. (1986). "High Tenacity Aramid Fibre", Technical Bulletin.

[13] Alwis K.G.N.C and C.J. Burgoyne (2008). "Viscoelasticity of aramid fibres", *Journal of Material Science*, Vol. 43: pp. 7091-7101.