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Allowable Long Term Stresses in Aramid Yarns

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ABSTRACT: Ever since advanced fibres were considered for structural engineering applications, it has been identified that their high strain capacity made them more suitable for use of prestressing tendons than as reinforcing bars. Their inherent resistance to corrosion made them ideal for use as external tendons, which in turn meant that they are ideal for use in repair and rehabilitation applications.

One of the limiting factors in such applications has been the lack of knowledge about high a force can be applied to the fibres for a long period of time. This directly affects the economics of the application, and because of uncertainty about the long-term properties can lead to very high factors of safety being applied.

The paper presents methods that have been used to measure the stress-rupture behaviour of two different aramid fibres, and shows how their properties can be extrapolated.

Testing is carried out using Time-Temperature Superposition, the Stepped Isothermal Method, and a method newly developed for this work, the Stepped Isostress Method. From these tests the activation energy for the effect of temperature on creep can be determined, and its constancy gives confidence that the extrapolations are not being taken too far.

The paper considers the implications of this work for predictions of the allowable stresses in prestressing tendons, stay cables for bridges, and some potential new applications for tethers in extreme conditions.

1 INTRODUCTION

Composite materials have been considered for use in structures for more than twenty years. Fibres such as aramid, carbon and glass have become increasingly popular in many structural applications due to their unique mechanical properties. They possess a combination of high strength, high stiffness and good resistance to creep and corrosion that should find use in external and internal prestressing, strengthening of structures through composite plates, composite bars as reinforcements, composites in the marine and railway industries and in ground engineering (Burgoyne, 1999).

This paper is limited to aramid fibres; their main attraction is their good resistance to corrosion by water, which would allow their use as external tendons or with much reduced concrete cover (Burgoyne, 1992). However, uncertainty about their ability to carry significant loads for a long period of time (stress-rupture) has meant that engineers have been reluctant to adopt them.

Prestressing tendons in concrete are most susceptible to this type of failure because they are tensioned against concrete immediately after the concrete has hardened, to provide the required compressive stresses, and the high force remains for the lifetime of the structure. They are the most heavily stressed elements in any structure, with typical force in steel tendons reaching 70% of the average breaking load (ABL). However, creep of concrete and relaxation of the tendons will reduce that figure to about 60% ABL after a few months, after which it remains constant (Abeles and Bardhan-Roy, 1981). Until recently, only high strength steel tendons have been used for prestressing concrete with ultimate tensile strengths reaching 1700 MPa. Aramids have a typical tensile strength about 3000 MPa. Aramids are tougher than carbon, so are easier to grip in a prestressing anchorage (Burgoyne, 1993); they therefore make an ideal material for use in prestressed concrete.

The common design lifetime for bridges is 120 years. It is impossible to conduct tests for these durations before using new materials. Tests carried out in testing machines are impractical for more than a few days, while tests using dead weights have high capital costs and take up valuable space. Therefore, the only way to assess new materials to determine the design life is to apply extrapolation techniques to short term test data.

Many materials exhibit stress rupture behaviour, in which the material will eventually creep to failure if a high load is applied continuously. For most materials, in which viscoelasticity is a thermally activated process that follows the Arrhenius equation, a linear relationship between the load and the logarithm of the time to failure can be expected (Curve A in Fig. 1). This curve does not, however, represent a decline in the short term strength. If specimens were loaded with a force P and then subsequently tested at different ages, up to the predicted rupture time t_r, the retained strength can be expected to follow Curve B in Fig. 1, showing that the short term strength is not significantly reduced (Rostasy and Schiebe, 1999).

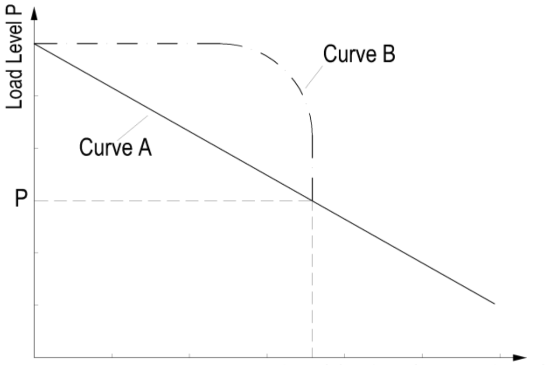

Figure 1. Stress rupture (Curve A) and residual strength (Curve B) for aramid fibres

Engineers need predictions of the stress-rupture lifetime relationship together with associated probabilities of failure of the material. This has been a problem for the use of aramids because existing test data is limited to a few months, while the contemplated load durations may be over a century. A commonly held view is that extrapolations should only be made for one decade on the log time scale. If longer extrapolations are made, much larger safety factors are frequently applied, which lowers the perceived strength of the material. Doubt about the extrapolation method can have a very real economic effect and can mean that a less suitable material is used simply because there is more confidence about its properties.

There is still an open debate about how design values should be obtained from the stress-rupture relationships. A commonly held approach is to obtain the characteristic value of the material at the prescribed design life and divide it by a partial safety factor. This factor for aramid fibres in some European design guides is proposed to be in the range between the value used for steel and that used for concrete. Because there is no significant difference between the aramids in production, as well as in failure modes, a material partial safety factor of 1.25 is proposed by FIB (2007). However, this factor can be higher if there is doubt about the applied extrapolation technique.

Many researchers have examined the stress-rupture behaviour of aramid fibres and have recommended their own stress limits. These range from 0.47 f_u after 50 years (Yamaguchi et al. 1997) to 0.66 f_u after 50 years (Ando et al.,1993). However, these creep-rupture predictions are based on conventional creep tests at ambient conditions and at high load levels (min 70 % ABL), when creep failures can be obtained in a short period of time. For lower stress levels extrapolation techniques have been used. The degree of extrapolation and the lack of test data introduce many uncertainties and therefore engineers should be very careful when using these figures in real structures.

2. CREEP TESTS ON ARAMID FIBRES

The creep data set used in this paper is part of a larger study (Giannopoulos, 2009) into the stress-rupture behaviour of two slightly different aramid fibres, Kevlar 49 and Technora. This study includes conventional creep tests at ambient conditions and accelerated tests at elevated temperatures and stress levels, using the Stepped Isothermal Method (Thornton et al, 1998; Giannopoulos and Burgoyne, 2008) and the Stepped Isostress Method (Giannopoulos and Burgoyne, 2009b).

Kevlar 49 is an aramid fibre, made by Du Pont, composed of a single monomer unit. Technora is a copolymer, made by Teijin using a slightly different process. One of the monomers units is the same as that in Kevlar, but the other is different. Both fibres obtain their high strength from the natural axial alignment of the polymer chain and hydrogen bonding between adjacent molecules, which encourages the formation of aligned liquid crystals.

Kevlar 49 and Technora yarns, available in reel forms supplied by a rope manufacturer, were used for all tests. The cross sectional area (*A*) of the yarns, after removing moisture, was found to be 0.17497 mm^2 and 0.12260 mm^2 respectively. The breaking load of Kevlar 49 and Technora was determined from 20 short term tensile tests and were 444.6 N for Kevlar 49 and 349.0 for Technora. These values are lower than might be expected, especially for the Technora, but are attributed to rewinding of the fibre onto spools and are typical of values found in real applications.

Conventional creep tests (CCT) at different stress levels (77.5 - 95% ABL) were carried out in a special room under constant temperature (25 ^oC) and humidity (50% RH) on both yarns. Each specimen was subjected to a constant load by hanging dead-weights from the bottom clamp. Four tests were performed at each load level and failure of the specimens was achieved in a reasonable time scale (a few months).

Stepped Isothermal Method (SIM) tests and Stepped Isostress Method (SSM) tests for Kevlar 49 and Technora yarns at different load levels (50 – 80% ABL) were carried out. Eight tests using

SIM and four tests using SSM were conducted at each load level. Experiments were not conducted below 50% ABL, since Kevlar 49 and Technora show a non-linear viscoelastic behaviour below 40% ABL (Alwis and Burgoyne, 2008) and the superposition principle would not have been applicable.

SIM testing involves loading a single specimen, under constant loads, with the temperature increased in a series of steps to accelerate the creep. Careful choice of temperature step and step duration allow the test to be completed in about 24 hours. At each temperature step a creep curve (strain vs. time) is obtained; these are then adjusted to compensate for the different temperature levels and a creep master curve at a reference temperature is produced. The activation energy of the viscoelastic materials can be determined.

In SSM testing, a similar approach is adopted but the acceleration is obtained by increasing the stress in steps while keeping the temperature constant. Additional stress provides energy to the system in an analogue of the effect of heat in SIM (Giannopoulos and Burgoyne, 2009b).

All tests have been carried out until failure. A complete set of stress-rupture data from conventional and accelerated creep tests is thus available for Kevlar 49 (111 tests) and Technora yarns (98 tests). The lifetime distribution is most simply shown by plots of applied load level vs. logarithmic time to failure (rupture time), as shown in Figures 2 and 3.

3 ANALYSIS OF DATA

It is observed from Figures 2 and 3 that for load levels between 50 and 95% ABL there is a linear increase of the logarithmic rupture time with decreasing applied load. This implies that the data follow a lognormal distribution and which can be modelled using a lognormal regression analysis. The data were fitted to such a distribution and tested with histograms, kernel density estimators, lognormal probability plots and the Lilliefors test. All confirmed the validity of the lognormal distribution (Crow and Shimizu, 1988).

The two fitted lognormal regression lines to the creep test data of the two materials shown in Figures 2 and 3 are:

$$\log (t_r) = 16.50 - 0.18\,P \qquad \text{for Kevlar 49} \tag{1}$$

$$\log (t_r) = 23.81 - 0.26\,P \qquad \text{for Technora} \tag{2}$$

where t_r is rupture time in hours
P is the load expressed as a % of ABL

The variation of the test data at all load levels about the two fitted regression lines is small ($r = 0.9905$ and $r = 0.9828$ for Kevlar 49 and Technora respectively).

The objective of this analysis is to produce a curve for mean time to failure and two curves corresponding to 5 and 95% confidence limits. Using the creep test data, the 90% prediction interval of the regression line is calculated and plotted also in Figures 2 & 3. Since the 90% prediction interval is the area in which 90% of all data points is expected to fall, i.e. 5% above and 5% below, then the lower 90% prediction interval line is also the 95% characteristic curve for the material. For Kevlar 49, only $0.05 \times 111 = 5.55$ points are expected to fall below the lower 90% PI line and this is confirmed from Figure 2. A similar observation is obtained for

Technora from Figure 3. The standard deviation in the logarithmic time to failure for Kevlar 49 is 0.32 decades, while for Technora it is 0.58 decades.

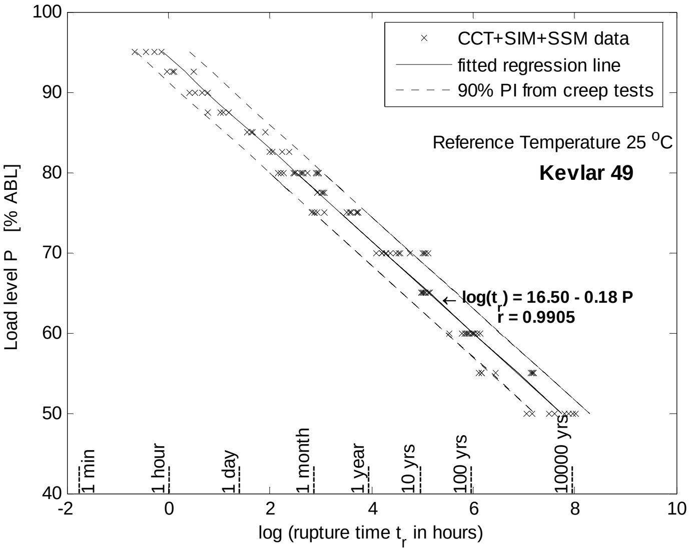

Figure 2. Rupture times from CCT, SIM & SSM tests for Kevlar 49

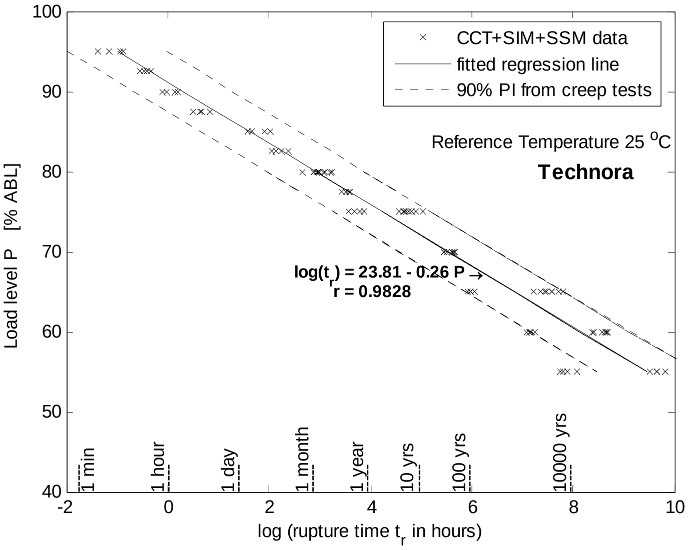

Figure 3. Rupture times from CCT, SIM & SSM tests for Technora

The characteristic value of the stress rupture lifetime will be 1.645 standard deviations below the mean. The 90% PI lines are drawn in Figures 2 & 3 assuming that they have the same slope as the mean line (i.e. the standard deviation is constant both as the load changes or the log time to failure changes). Figure 4 shows how the standard deviation of the short term strength (σ_P) can be compared with the standard deviation of the logarithmic rupture time ($\sigma_{\log(tr)}$), assuming a constant slope.

The constant slope and the constant standard deviation of the log rupture time would predict a short term strength variability of 7.9 and 7.8 N for Kevlar 49 and Technora respectively. A very useful conclusion that can therefore be deduced that the dispersion in the logarithmic rupture time values under a constant axial load can be explained from the dispersion in the static breaking load values. An analogous conclusion was drawn for fatigue tests by van Leeuwen & Siemes (1979) and Holmen (1979).

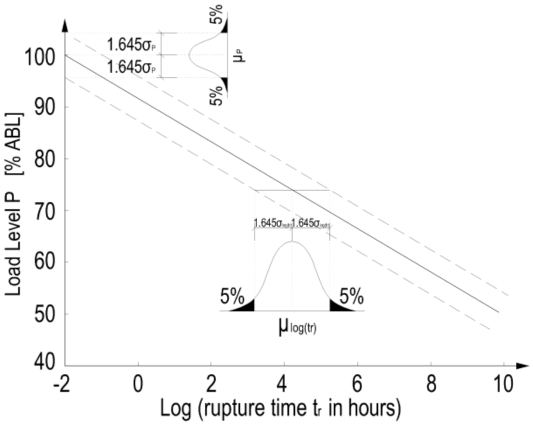

Figure 4. Relation between the dispersion in the static breaking load values and rupture times

The 95% characteristic curves for Kevlar 49 and Technora can be used for design purposes as the characteristic strength f_{fk} for any prescribed design life. To obtain the design strength f_{fd} a material partial safety factor γ_f should be applied. Because no extrapolation is carried out, a less conservative factor can be applied than the one proposed in FIB. However, to obtain such a value a full reliability analysis would have to be carried out (CEN, 1990). A simpler approach used in many Japanese Codes is adopted (JSCE, 1997), in which the design strength f_{fd} is taken to be 3 standard deviations below the mean, which corresponds to a 99.73% PI line. For a design life of 50 years (t_r=50 years) at 25 °C, the resulting values are:

$$f_{fk(50years)} = 58.6\%\ \text{ABL} \qquad f_{fd(50years)} = 56.3\%\ \text{ABL} \qquad \text{for Kevlar 49} \tag{3}$$

$$f_{fk(50years)} = 65.8\%\ \text{ABL} \qquad f_{fd(50years)} = 63.1\%\ \text{ABL} \qquad \text{for Technora} \tag{4}$$

These values correspond to a partial material safety factor of 1.04 applied to the characteristic value.

4. EFFECT OF TEMPERATURE

It should be pointed out that the fitted regression line for Kevlar 49 and Technora, shown in Figures 2 & 3, have been obtained for a reference temperature of 25 °C. It is possible to shift these lines to correspond to a different temperature T. The amount of shift $\log(\alpha_T)$ is determined from the Arrhenius equation (Arridge, 1975).

$$\log(\alpha_T) = \frac{E}{2.30R}\left(\frac{1}{T} - \frac{1}{T_R}\right) \tag{5}$$

where E is the activation energy of the reaction ($Jmol^{-1}$)
h is the universal gas constant (= 8.314 $JK^{-1}mol^{-1}$)
T is the temperature (K)
T_R is the reference temperature (K)

Activation energies for Kevlar 49 and Technora were determined during the SIM testing and found to be 119 and 138.6 $kJ \cdot mol^{-1}$ respectively (Giannopoulos, 2009).

By inserting the above equation into the stress-rupture equations (Eq. 1 & 2) new relationships are obtained which take account of the temperature. For example, for Technora,

$$\log(t_r) = +0.51 + \frac{7248}{T} - 0.26P \qquad \text{for Technora} \qquad (6)$$

Applying the above relationships, load – log (rupture times) lines are determined at 4 different temperatures (0, 25, 40, 60 °C) as shown in Figure 5 for Technora; a similar figure can be made for Kevlar. Increasing the reference temperature decreases the rupture time as expected.

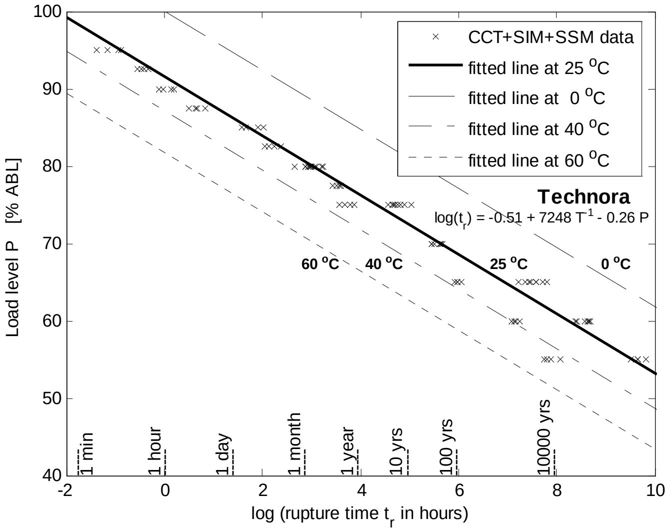

Figure 5. Load - rupture times for Technora yarns at various reference temperatures

5 CONCLUSIONS

This paper has shown that it is possible to conduct accelerated tests on organic fibres which allow the long-term creep rupture behaviour to be established with confidence. These Stepped Isothermal Method and Stepped Isostress Method tests are shown to give good agreement with conventional creep testing but can be carried out much more rapidly, and at lower stress levels where conventional creep testing to failure is impractical. The effect is that it is now possible to predict lifetimes of these fibres, and of ropes or tendons made from them, with much more certainty than was hitherto possible.

The methods have been applied to two aramid fibres which are similar but have slightly different chemical and physical structures. The results have shown that these differences are reflected in significant differences in their long-term properties. It has been shown that

Technora has more variability than Kevlar 49, and a higher viscoelastic activation energy, which means that it is less likely to be affected by stress rupture at practical stress levels.

It has been shown that the test data can be used to predict allowable stresses for these materials in applications where they are subjected to high permanent stresses, the most obvious examples of which are prestressing tendons and bridge stay cables.

It is now possible to make use of these exciting materials in applications where lack of material knowledge has made engineers overly cautious about their use.

An extended version of this paper is to be found elsewhere (Giannopoulos and Burgoyne, 2009a)

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