Design Criteria for Aramid Fibres

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ABSTRACT

Aramid fibres should have many structural applications; they should be 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. However, uncertainty about their ability to carry significant load for a long period of time has meant that engineers have been reluctant to adopt them.

Two new techniques (Stepped Isothermal Method and Stepped Isostress Method) are now available and allow accelerated testing to be carried out at low stress levels, in such a way that the long term creep and creep rupture properties can be determined without having to extrapolate more than one decade on a log-time scale. Such tests have now been carried out on two slightly different aramid fibres, Kevlar 49 and Technora.

The paper shows how this information can be used to predict the safe operating stresses for these fibres when under sustained load, which is precisely the sort of application for which they are most economically suited. The effects of yarn variability are considered, as are the effects of different temperatures and varying loadings. The aim is to be able to predict the behaviour when subject to load durations of 100 years or more, without having to provide excess material because of a lack of applicable test data.

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. 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 are some of the areas where fibrous composites can be used. A detailed review of the applications of different types of composites can be found elsewhere [1].

The scope of this paper is limited to aramid fibres. Aramids can be used as tendons in prestressed concrete, as stay cables in bridges and as ropes in the marine industry, and for a number of other structural applications, as described elsewhere [2]. The main attraction is their good resistance to corrosion by water, which would allow their use as external tendons or with much reduced concrete cover. 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 in place for the lifetime of the structure.

Tendons are the most heavily stressed elements in any structure, with typical forces 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 sensibly constant [3]. 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, as shown in Fig. 1. Aramids are tougher than carbon, so are easier to grip in a prestressing anchorage [4]; they therefore make an ideal material for use in prestressed concrete.

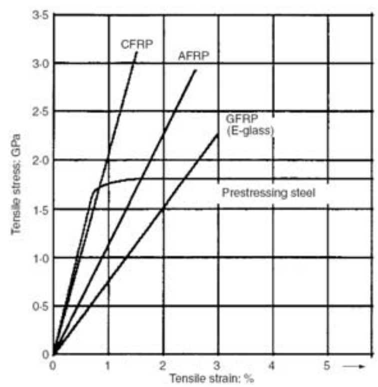

Figure 1. Stress vs. strain curves for Aramid Fibre Reinforced Polymer compared with prestressing steel [1]

At the present time aramid tendons are several times more expensive than steel. However, their good resistance to corrosion and the consequent assurance of long-term durability can compensate the additional first cost if the whole-life costing is considered [5]. The whole-life cost is closely related to the allowable long-term stress that can be applied to the tendons, which is governed by the stress-rupture relationship.

According to most design codes and guidelines, the common design lifetime for residential or office buildings is 50 years and for bridges is 120 years. These figures are notional and very often society feels aggrieved if buildings or bridges need to be refurbished due to durability failures at any age. On the other hand, it is impossible to conduct tests for these durations before using new materials. Tests carried out in testing machines rarely last for more than a few days because of the expense of tying up the machine, while tests using dead weights have high capital costs and take up valuable space. Therefore, the commonest way to assess new materials to determine the design life is to apply extrapolation techniques to short term test data. There is no long-term data.

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 [6]. However, this factor can be higher if there is doubt about the applied extrapolation technique.

Stress-limits proposed by various researchers

Many researchers have examined the stress-rupture behaviour of aramid fibres and have recommended their own stress limits. Ferer and Swenson [7] recommended empirically a safety factor of 5 for ropes of Kevlar fibres, but they were contemplating marine rope applications where there is significant uncertainty in the loading. Prestressing tendons always have much lower factors of safety because the loading is under direct engineering control. Guimaraes [8] has conducted creep tests on parallel-lay aramid ropes; he determined a relationship between creep and rupture time and proposed a stress limit of 0.54 f_u after 50 years. Yamaguchi et al. [9] carried out creep tests for 1000 hours on FRP rods made with aramid fibres and found a critical stress due to stress-rupture of 0.47 f_u after 50 years. Ando et al. [10] tested tendons made from aramid fibres and found a critical stress of 0.66 f_u after 50 years. Gerritse and Taerwe [11] proposed limiting the initial stress in prestressing elements to 0.55 f_u. Alwis and Burgoyne [12] tested aramid yarns at 50% and 70% ABL using accelerated techniques and found a stress limit of 0.64 f_u for 50 years.

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.

Stress-limits by design codes and guidelines

Currently, design guides for FRP reinforcement exist in Japan, Canada, Italy, the USA and the UK. In Norway, provisional design recommendations have been developed. Table 1 summarises the strength reduction factors used in international guidelines or codes due to environmental actions and sustained load.

The design guidelines of the British Institution of Structural Engineers (IStructE) propose only one factor that reduces the material strength and this takes into account the effects of environment, sustained stress and other general uncertainties of the material. Other codes, e.g. American Concrete Institute (ACI) 440, Canadian Highway Bridge Design Code CHBDC, Italian Standard CNR DT2005, Japanese Society of Civil Engineers (JSCE), Norwegian Standard NS 3473 and the STF 22A98741 propose two separate reduction factors to account for the deterioration caused by environmental and long–term effects.

It is worth mentioning that the combined effects of environmental deterioration and sustained loads are considered by multiplying together the two load factors which can result in very low permissible stresses.

Table 1. Recommended stress-limits for aramid fibres from various guidelines and codes

<table>
<tr><th rowspan="2">Guidelines or codes</th><th colspan="2">Reduction factor
(% of the short-term tensile strength)</th></tr>
<tr><th>environmental deterioration</th><th>sustained load</th></tr>
<tr><td>ACI 440</td><td>0.80 - 0.90</td><td>0.24 - 0.27</td></tr>
<tr><td>ISE</td><td colspan="2">0.50</td></tr>
<tr><td>CHBDC</td><td>0.6</td><td>0.35 - 0.40</td></tr>
<tr><td>CNR</td><td>0.80 - 0.90</td><td>0.50</td></tr>
<tr><td>JSCE</td><td>0.87</td><td>≤ 0.7</td></tr>
<tr><td>NS 3473</td><td>0.90</td><td>Not specified</td></tr>
</table>

It is clear that these differences in design approach to FRP durability make it difficult for the international construction community to have confidence in predictions of FRP service life in aggressive environments. Consequently, a more rigorous approach to durability specification needs to be adopted.

FIB [6] presents a new methodology which takes into account all the environmental influences on FRP and allows engineers to choose more realistic margins of safety. It is proposed that aramid fibres can be designed for durability on the basis of a simple strength equation. The characteristic long term strength f_{fk} of fibres is linked to the characteristic short term strength $\mathrm{f_{fk0}}$ by the following equation

$$f_{fk} = f_{fk0} / \eta_{env,t} \tag{1}$$

The long term strength f_{fk} is affected by environmental and time effects, e.g moisture, alkali, temperature and creep, while the short term strength f_{fk0} has no such effects. The value of the environmental strength reduction factor $\eta_{env,t}$ depends on the severity of the exposure environment.

The environmental factor $n_{env,t}$ can be determined accurately [13] if the 1000 hour tensile strength $f_{fk1000h}$ is known and it is assumed that the strength reduction continues at the same rate on a logarithmic time scale. R_{10} is the standard reduction of tensile strength in percent per logarithmic decade (i.e. slope of Fig. 2).

$$\eta_{env,t} = f_{fk0} / [f_{fk1000h} \cdot ((100-R_{10})/100)^{n}] \tag{2}$$

If $f_{fk1000h}$ is not known, the above approach is modified by Weber [13] and the following equation is recommended

$$\eta_{env,t} = 1 / ((100-R_{10})/100)^{n+2} \tag{3}$$

The exponent n in these equations is the sum of four influence terms.

$$n = n_{mo} + n_T + n_{SL} + n_d \tag{4}$$

Table 2. Four influence terms at standard and test conditions

Variable	Dependency	Standard Conditions	Value at Stand. Conditions	Test Conditions	Value at test Conditions
n_{mo}	moisture	80% RH	0.0	50% RH	-1.0
n_T	temperature	5 to 15 ^oC	0.0	25 ^oC	1.0
n_{SL}	service life	100 years	3.0	50 years	2.7
n_d	diameter	as tested	0.0	as tested	0.0

Details of these influence terms are given elsewhere [6]. The exponent n for standard exposure conditions is 3 and for the relevant conditions during the tests reported here is 2.7.

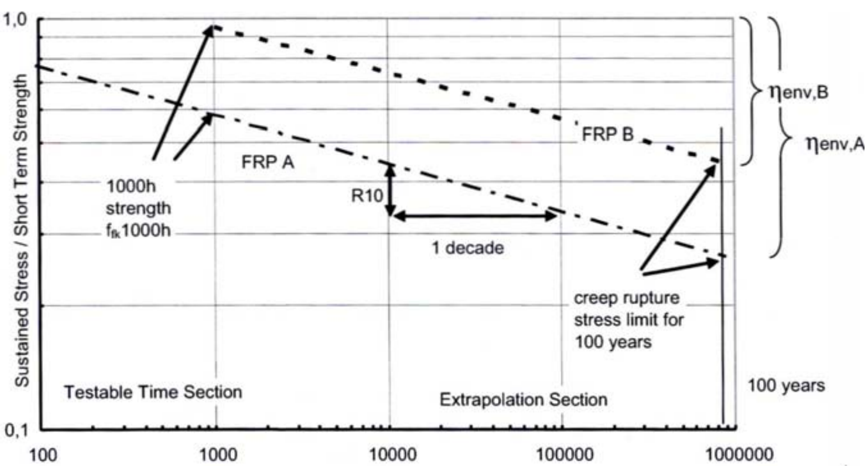

Figure 2. Environmental strength reduction factor and 1000h strength for two FRP materials with different durability [6]

This paper examines the long-term stress-rupture behaviour of aramids, using new test results on Kevlar 49 and Technora yarns. These data, obtained at low stress levels, albeit using an accelerated testing procedure, give more assurance that the extrapolations to structural lifetimes can be carried out with greater confidence, without the application of penalising high factors of safety. Therefore, stress-limits for a service-life of 50 or 100 years are proposed for aramid fibres and compared with the values reported in literature and in existing international design guidelines.

CREEP TESTS ON ARAMID FIBRES

The creep data set used in this paper is part of a larger study [14,15] 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 [14,15] and the Stepped Isostress Method [14,16].

Kevlar 49 and Technora yarns, available in reel forms, were used for all tests. 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 (445 N for Kevlar and 349 N for Technora) was determined by testing twenty different specimens for each material with a standard deviation σ of 8.22 N and 6.75 N for Kevlar 49 and Technora respectively. All values obtained are in agreement with the literature [17,18].

Conventional creep tests (CCT) at different stress levels (77.5 - 95% ABL) were carried out in a special room under constant temperature (25 ^{o}C) 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 [14,19] and the superposition principle would not have been possible. A detailed description of the tests is presented elsewhere [14] but the methods are summarised below.

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.

All tests have been carried out until failure of the specimens. Therefore a complete set of stress-rupture data from conventional and accelerated creep tests is 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 Fig. 3.

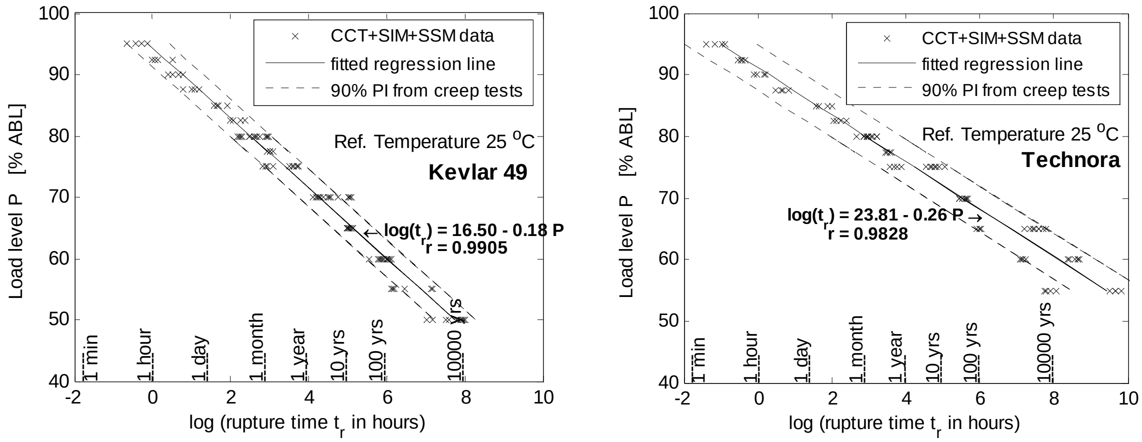

Figure 3. Rupture times from CCT, SIM & SSM tests
with 90% Prediction Interval for Kevlar 49 and Technora

RESULTS AND DISCUSSION

It is observed from Fig. 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. Many researchers [8, 20-23] have used lognormal distributions to analyze life data; the validity of this model can be checked by several ways; histogram, kernel density estimator, lognormal probability plot and Lilliefors test. More details for the application of those tests are given elsewhere [14].

Creep data for Kevlar 49 and Technora were fitted to a lognormal distribution and the test methods described above were used to check the validity of the model. From Fig. 4 for Kevlar 49 and Technora, it can be observed that the two histograms and kernel density plots have a bell shape indicating the normality of the two data sets. Also, the points on the lognormal probability plots form a nearly linear pattern, which indicates that the lognormal distribution is a good model for these data sets. Finally, the two creep data sets were checked using Lilliefors test, which also confirmed that the data distribution was lognormal.

The two fitted lognormal regression lines to the creep test data of the two materials are shown in Fig. 3 are:

$$\log(t_r) = 16.50 - 0.18\,P \qquad \text{for Kevlar 49} \qquad (5)$$

$$\log(t_r) = 23.81 - 0.26\,P \qquad \text{for Technora} \qquad (6)$$

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).

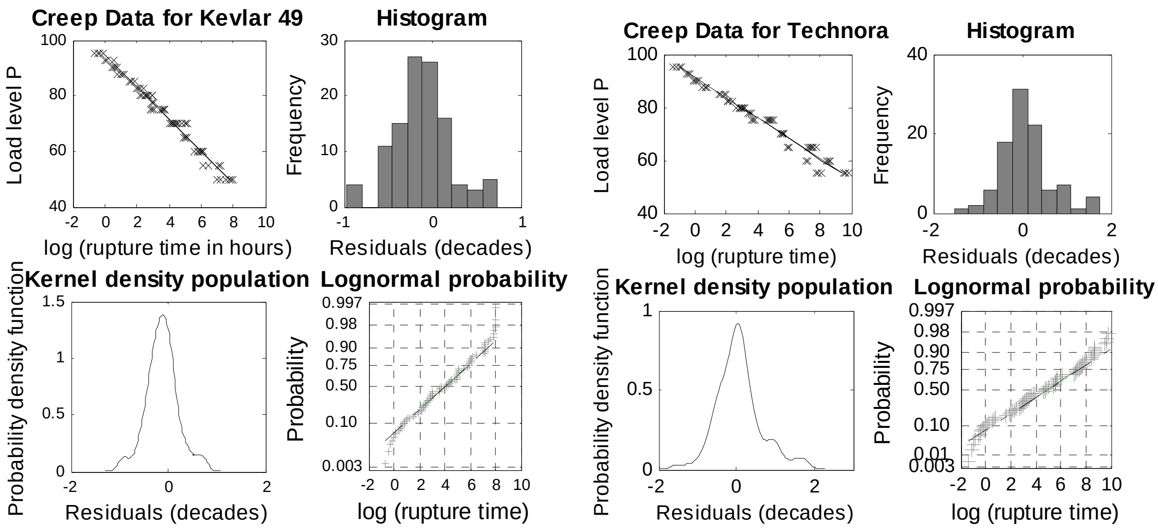

Figure 4. Lognormal distribution and validity checks of creep data for Kevlar & Technora

The objective of this analysis is to produce a curve for mean time to failure and the corresponding 5 and 95% confidence limits. Using the creep test data, the 90% prediction interval of the regression line is calculated and plotted also in Fig. 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 0.05×111 = 5.55 points are expected to fall below the lower 90% PI line and this is confirmed from Fig. 3. A similar observation is obtained for Technora. The standard deviation in the logarithmic time to failure for Kevlar 49 is 0.32 decades, while for Technora it is 0.58 decades.

The characteristic value of the stress rupture lifetime will be 1.645 standard deviations below the mean. The 90% PI lines are drawn in Fig. 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). 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. These values are in agreement with values obtained from the short term tensile testing of 20 specimens.

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 that proposed in FIB. However, to obtain such a value a full reliability analysis would have to be carried out. A simpler approach adopted in many Japanese Codes 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% ABL $f_{fd(50years)}$ = 56.3% ABL for Kevlar 49 (7)

$f_{fk(50years)}$ = 65.8% ABL $f_{fd(50years)}$ = 63.1% ABL for Technora (8)

These values correspond to a partial material safety factor of 1.04 applied to the characteristic value, and are of the same order as the values given in Table 1 by various researchers.

The design strength f_{fk} for a 50 year design life obtained from the creep data (Eq. 7 & 8) can be compared with the stress limit obtained from the refined approach of FIB [6]. As explained, the value of the environmental strength reduction factor $\eta_{env,t}$ can be calculated for the specific environmental conditions and for a prescribed design life. The terms for moisture condition, temperature, service life and diameter of specimen are 50% RH, 25 ^{o}C, 50 years and 'the same size as tested' respectively. Therefore, the influence factor n is 2.7, as shown in Table 3.

In addition, the characteristic strength at 1 and 1000 hours and the slope R10 for the two materials from Fig. 3 are given in Table 3.

Table 3. Characteristic strength at 1 and 1000 hrs and slope R_{10}

Material	f_{tk1}	f_{fk1000}	R_{10}
	[% ABL]		
Kevlar 49	96.85	73.94	5.6
Technora	96.82	76.41	3.7

Following the refined approach of FIB [6] and using Eqs. 1 and 2, the following $\eta_{env,t}$, $f_{fk(50\ yrs)}$ and $f_{fd(50\ yrs)}$ values are obtained for the two materials:

$\eta_{env,t}$ = 1.52 $f_{fk(50\ yrs)}$ = 63.7% ABL $f_{fd(50\ yrs)}$ = 51.0% ABL for Kevlar 49 (9)

$\eta_{env,t}$ = 1.40 $f_{fk(50\ yrs)}$ = 69.2% ABL $f_{fd(50\ yrs)}$ = 55.4% ABL for Technora (10)

The design strength values (Eqs. 9 and 10) are lower than the values obtained from the current study (Eqs. 7 and 8), showing that the FIB approach is more conservative than the current results. This was expected, since FIB is extrapolating creep data at 1000 hours to predict the stress rupture behaviour after 50 years using a penalising partial factor (γ_f=1.25) due to uncertainties (Fig. 5). In the current study, data is available at lower load levels and therefore a less conservative partial factor can be applied (γ_f=1.04).

The difference between the 50 years design life (for buildings) and 120 years design life (for bridges) is very small, as can be seen in Fig. 5.

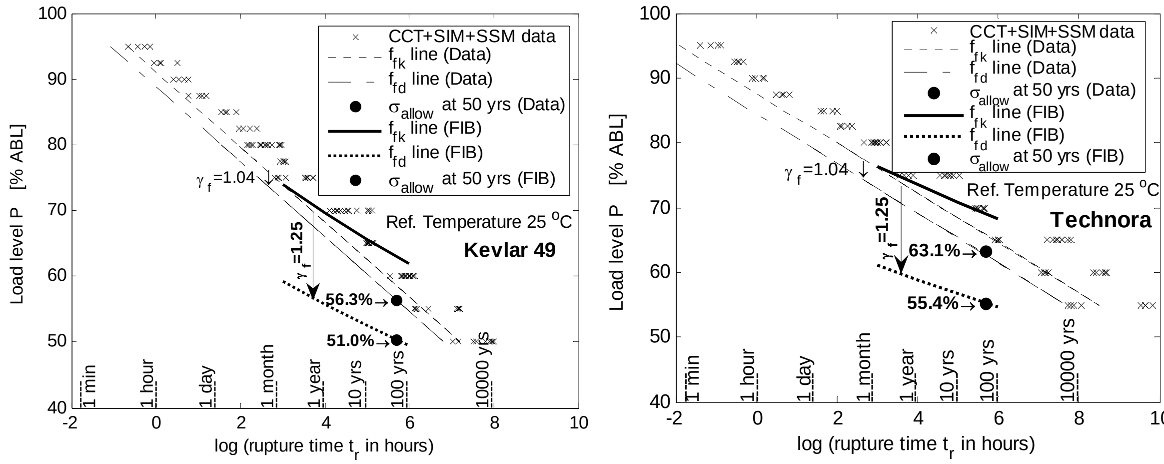

Figure. 5 Design strength obtained from current data and from FIB approach
for a 50 years design life for Kevlar 49 and Technora

Effect of temperature

It should be pointed out that the fitted regression lines for Kevlar 49 and Technora, shown in Fig. 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 (α_T) is determined from the Arrhenius equation [24]

$$log\,(a_T) = \frac{E}{2.30R}\left(\frac{1}{T} - \frac{1}{T_R}\right) \tag{11}$$

where E is the activation energy of the reaction ($J{\cdot}mol^{-1}$)
h is the universal gas constant (= 8.314 $J{\cdot}K^{-1}{\cdot}mol^{-1}$)
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 [14,15].

By inserting the above equation into the stress-rupture equations (Eq. 5 and 6) new relationships are obtained which take account of the temperature:

$$log\,(t_r) = -\,4.54 + \frac{6270}{T} - 0.18\,P \qquad \text{for Kevlar 49} \tag{12}$$

and similarly

$$log\,(t_r) = +\,0.51 + \frac{7248}{T} - 0.26\,P \qquad \text{for Technora} \tag{13}$$

Applying the above relationships, load – log (rupture times) lines are determined at 4 different reference temperatures (0, 25, 40, 60 °C) as shown in Fig. 6 for the two materials. Increasing the reference temperature decreases the rupture time as expected.

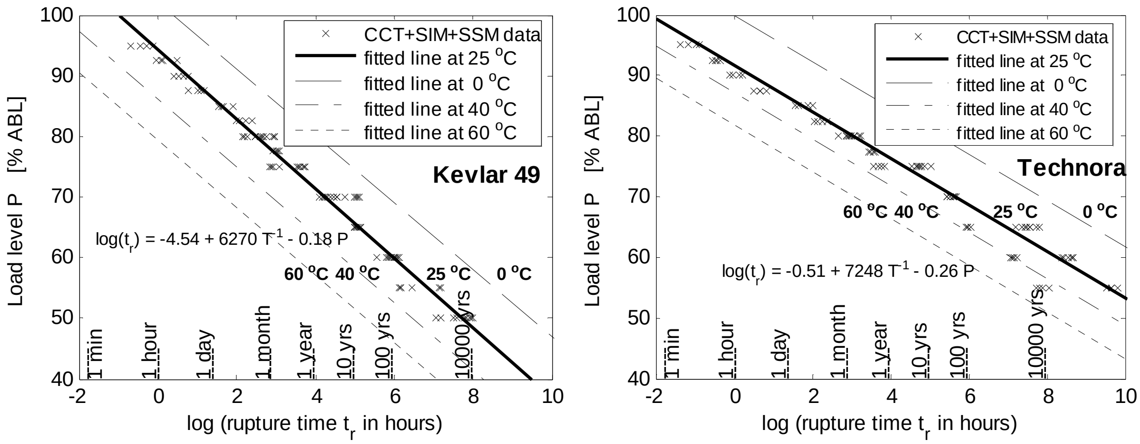

Figure. 6 Load - rupture times for Kevlar 49 & Technora yarns at various ref. temperatures

CONCLUSIONS

No one has, or ever will, conduct a conventional 50 year stress rupture test. 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 reasonable 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; these differences are reflected in the long-term properties of the materials. The test data can be used to predict allowable stresses in applications subjected to high permanent stresses, the most obvious examples of which are prestressing tendons and bridge stay cables. The effects of temperature have also been studied and modified stress-rupture expressions have been obtained taking into account temperature. 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.

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