ADVANCED COMPOSITE MATERIALS IN BRIDGES AND STRUCTURES
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MATÉRIAUX COMPOSITES D'AVANT-GARDE POUR PONTS ET CHARPENTES
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STRESS-RUPTURE DATA FOR ARAMID FIBRES

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ABSTRACT

A model for lifetime prediction of a parallel-lay aramid rope is developed based on stress-rupture test results of specimens of different sizes. The tests were conducted at ambient temperature with specimens subjected to static stress levels ranging from 67.3% to 84.4% of the ultimate tensile strength and times-to-break extending to nine months. The Weibull statistical distribution was selected to describe the scatter of the experimental data which allows the assignment of probability levels for the estimated lifetime.

INTRODUCTION

Aramid fibres have been used in the production of parallel-lay ropes which can be ideal for applications as tension members in many types of structures such as prestressed structures, cable stayed bridges, cable supported roofs and mooring lines for offshore platforms. In situations where the weight and the resistance to corrosion are determining factors in the choice of material, the use of these ropes can be particularly advantageous.

It is clear that a thorough understanding of the stress-rupture behaviour of these ropes is of primary concern for such applications, since the permanent operating stress of aramids will usually be governed by this phenomenon.

One type of rope constructed with aramid fibre is commercially known as Parafil (Parafil is a trade name of Linear Composites Ltd, UK), which is produced in different versions depending on the type of fibre in core. The rope considered in this investigation is Type G Parafil, which consists of parallel yarns of Kevlar 49 (Kevlar is a trade name of EI Du Pont de Nemours) encased by a polymeric sheath. The specific gravity of Kevlar fibre is 1.44; in rope form, however, it reduces to 0.98 due to the presence of air between filaments. This rope has a linear stress-strain relationship up to failure, with a nominal tensile strength of 1926 MPa and elastic modulus around 118000 MPa. Creep strains are considered very low for a polymeric material; they will not exceed 0.12 of the initial strain in normal use (Guimarães and Burgoyne, 1992). Additional information on the properties most relevant to structural applications can be found in (Burgoyne, 1988).

A tentative model for describing the stress-rupture behaviour of parallel-lay aramid ropes is developed from the lifetime data for 1.5, 3 and 60 tonne ropes measured at ambient temperature. A theoretical basis, which is essential to any model intended for extrapolation purposes, is provided by existing theories on the fracture behaviour of polymers. These theories indicate the most adequate functional form for the model. The Weibull statistical distribution was selected to describe the scatter of the experimental data. The combination of a theoretical functional form with this statistical distribution allows the assignment of probability levels which are of great interest in engineering applications.

EXPERIMENTAL PROCEDURE AND RESULTS

The specimens used in this investigation were Type G Parafil ropes with nominal breaking loads of 1.5 tonne, 3 tonne and 60 tonne, having cross-sectional areas of yarns in the core of 7.64 mm^2, 15.28 mm^2 and 305.5 mm^2 respectively. The tensile strength of the specimens, obtained from short-duration tests, are 2403 MPa (with standard deviation of 70.7 MPa), 2200 MPa (st. dev. = 45.3 MPa) and 1954 MPa (st. dev. = 66.0 MPa) for the 1.5, 3 and 60 tonne ropes respectively. The tests were conducted on specimens subjected to constant loads at ambient temperature (20 ± 3) °C. A detailed description of the specimens and test procedure is given by Guimarães and Burgoyne (1992) for the 1.5 and 3 tonne ropes, and by Chambers and Burgoyne (1990) for the 60 tonne ropes. (The specimens are labelled here as in the original papers, for consistency). The results of the stress-rupture tests are given in Table 1.

THEORETICAL CONSIDERATIONS ON A STRESS-RUPTURE MODEL

Two general theories have been used to describe the stress rupture behaviour of polymers; the molecular and fracture mechanics theories. Both theories consider fracture as a kinetic phenomenon but differ in the rate controlling step in the breakdown phenomenon. Information on these theories can be found in Zhurkov (1965), Bueche (1958), Coleman and Knox (1957) and Christensen and Wu (1981).

Probably the most widely used molecular model has been the one developed by Zhurkov (1965) and Zhurkov and Korsukov (1974). They obtained a relationship between lifetime, applied tensile stress and temperature of the form

$$t_b = t_o \exp[(U - B\sigma) / kT] \qquad [1]$$

where t_b is the stress-rupture life, t_o is the period of the thermal oscillations of bonded atoms, U is the activation energy, B is a coefficient related to the actual stress on the atomic bonds, k is the Boltzman's constant, σ is the applied stress and T is the absolute temperature.

It is well accepted that this theoretical model offers a good explanation of the stress-rupture behaviour of materials in general. The determination of its physical constants, however, presents some difficulties in practice. To overcome this, the development of a model for a particular material can be approached by assuming the theoretical model for the functional form, with its physical constants being viewed as fitting parameters, determined from tests.

The model formulated here follows such a procedure. Construction of the model involves three steps; namely, the selection of an adequate functional form, the selection of a statistical distribution for the experimental data and, finally, the determination of the stress dependence of the parameters of the distribution.

A MODEL FOR LIFE PREDICTION OF PARALLEL-LAY ARAMID ROPES

Relating the Lifetime Data of 1.5, 3 and 60 tonne Ropes

The static strength of the ropes considered in this study decreases as the cross-sectional area increases (Guimarães, 1988), becoming effectively constant for larger ropes. This behaviour is predicted by statistical bundle theory, which indicates that the static strength of a bundle is less than the average strength of the fibres taken individually. The statistical bundle theory (Phoenix, 1976 and 1978) also predicts that, under the same stress, the time to bundle failure is less than that of a single fibre. In a comparison between Kevlar 49 fibre bundles of various sizes, Phoenix (1976) showed that the stress-rupture curves for the bundles were parallel and the times to failure become approximately equal if the stress on the bundle is reduced by a factor equal to its strength efficiency (Strength efficiency is defined as the ratio of the mean bundle strength to mean fibre strength). Therefore, the natural way of representing the lifetime data for various sizes of ropes is by normalising the applied stress by the tensile strength. Indeed, the lifetime data on 1.5, 3 and 60 tonne ropes shown in Fig. 1 are in fair agreement not only between themselves, but also with the median lifetime of Kevlar 49 filaments (Wagner et al, 1986), the most probable lifetime of Kevlar 49 bare yarns (Howard and Parratt, 1985) and the median lifetime of Kevlar 49 pressure vessels made from the worst spool (Glaser et al, 1984).

Functional Form for the Model

The function selected to represent the relationship between applied stress and time-to-break of the ropes is the exponential breakdown rule resulting from the model proposed by Zhurkov (1985) (Eq. 1), which can be written in the form

$$\ln(t_b) = \alpha + \beta f \qquad [2]$$

In the above equation α and β are constants, to be determined from test results, and f is the normalised applied static stress.

Statistical Distribution of Lifetime Data for the Ropes

An important development in the prediction of lifetimes of polymers is the combination of a theoretical model with Weibull statistics methods. The main advantage of this approach is that probability levels of failure can be assigned which are of great importance in structural engineering applications. The Weibull distribution has emerged as the most suitable statistical distribution to describe the stress-rupture behaviour of Kevlar 49 fibres (Chiao et al, 1974; Phoenix and Wu, 1983; Glaser et al, 1984; Wagner et al, 1986). This implies that the lifetime data for ropes, which are bundles of yarns, should also follow the same distribution. For the time being the Weibull distribution will be assumed to be adequate for aramid ropes.

The cumulative distribution function of the Weibull distribution, in its two-parameter form, is represented by the equation (with the location parameter taken as zero)

$$P(x) = 1 - \exp\left[-\left(\frac{x}{r}\right)^s\right] \qquad [3]$$

where s and r are the shape and scale parameters. In problems dealing with lifetime, $P(x)$ is the probability of failure and x is the lifetime (for a detailed discussion of this distribution, see for example (Lipson and Sheth, 1973). The parameters s and r can be estimated by the method of maximum likelihood (ML) using the expressions (Talreja, 1981):

$$\frac{1}{s} - \frac{\sum x_i^s \ln(x_i)}{\sum x_i^s} + \frac{\sum \ln(x_i)}{n} = 0 \qquad [4]$$

$$r^s = \frac{\sum x_i^s}{n} \qquad [5]$$

Ideally, the number of data points at each stress level should be high enough to provide accurate estimates of these parameters. In the present study, minor adjustments were made in order to obtain the maximum number of data points at the same stress level; this was done in an approximate way by grouping together those data points with f values within the range f_{mean} $(1 \pm CV)$ where CV is the ratio between the standard deviation and the ultimate tensile strength of the ropes. Table 1 shows the f_{mean} values considered and the corresponding marginal maximum likelihood estimates of the shape and scale parameters obtained by means of Eqs. [4] and [5] (Marginal estimate for a given stress level is an estimate computed based solely on the data corresponding to that stress level).

Table 1 - Stress-rupture data and marginal maximum likelihood estimates of Weibull parameters for aramid ropes

Specimen	NBL (ton)	f (%UTS)	f_{mean} (%UTS)	t_b (days)	Number of specimens	s	r (days)
3	60	83.9	84.4	0.019	3	0.70	0.28
8	60	84.9		0.112			
7	60	84.3		0.941			
4	60	78.5	80.9	0.083	8	0.64	3.31
C93-1	3	81.6		0.418			
C93-2	3	81.6		0.493			
12	60	79.0		0.789			
C93-7	3	81.6		1.585			
C93-5	3	81.6		3.619			
C93-8	3	81.6		11.49			
C93-6	3	81.6		18.71			
15	60	76.4	75.9	0.715	10	1.09	31.05
C87-1	3	75.8		3.193			
13	60	73.9		11.16			
6	60	75.0		11.96			
C87-5	3	75.8		27.53			
C87-6	3	77.1		36.36			
C87-2	3	75.8		39.51			
C87-7	3	75.8		45.36			
C87-8	3	77.1		53.20			
C87-3	3	75.8		72.92			
R91-3	1.5	73.3	73.2	3.453	6	1.24	19.08
R91-1	1.5	73.3		4.934			
R91-4	1.5	73.1		9.679			
R91-5	1.5	73.1		17.30			
R91-2	1.5	73.3		25.31			
R91-6	1.5	73.3		45.65			
R85-1	1.5	67.8	67.3	35.27	4	1.98	171.28
16	60	67.1		155.15			
R85-2	1.5	67.6		164.76			
C76-1	3	66.8		255.32			

NBL = Nominal breaking load; t_b = time-to-break; f = applied stress expressed as % of ultimate tensile strength; f_{mean} = mean value of f values; s = shape parameter; r = scale parameter

Stress Dependence of the Parameters of the Distribution

The stress dependence of the shape and scale parameters is determined by estimating them at various stress levels and choosing adequate functions to represent the relationship between the parameters and applied stress.

Table 1 shows that the values of r and s are stress dependent, with both parameters decreasing with an increase of the stress level. The exponential representation [Eq. 2] was selected to express the stress dependence of the scale parameter r. Similarly, an exponential function was also found to give a good representation of the stress dependence of the shape parameter s. The resulting equations, determined by performing a least square analysis, are

$$s = 166\, e^{-0.066 f} \qquad [6]$$

$$\ln(r) = 40.3 - 0.35 f \qquad [7]$$

(where f is expressed as percentage of ultimate tensile strengh and r is in seconds: the correlation coefficients are -0.955 for both equations)

Lifetime Prediction

An equation to estimate the lifetime corresponding to a given probability of failure can now be established. Substituting Equations [6] and [7] into Equation [3] and rearranging, the following expression is obtained:

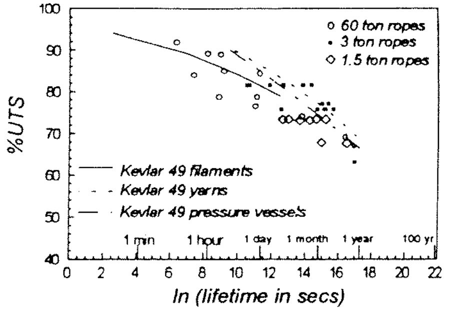
$$\ln(t_b) = 0.006\, e^{0.066 f} \ln[-\ln(1-P)] - 0.35 f + 40.3 \qquad [8]$$

which estimates the lifetime t_b in seconds, corresponding to a probability of failure P, when the material is subjected to a static stress level f expressed as a percentage of the ultimate tensile strength.

The lines corresponding to 5%, 50% and 95% probability of failure obtained from the above equation are plotted with the experimental data in Fig. 2, which shows that the model gives a good representation of the scatter of the data. The figure also shows that the results obtained from Eq.[8] are similar to those given by the model for Kevlar 49 pressure vessels developed by Glaser et al (1984). Lines corresponding to other probabilities of failure, which are of interest for engineering use, can be plotted from Eq.[8]. For example, for a lifetime of 50 years, there is a probability of failure of 5% when the material is subjected to a stress level of 53% UTS; for 10^{-3} probability of failure the corresponding stress level is 51% UTS; for 10^{-6} probability of failure the corresponding stress level is 49% UTS.

CONCLUSIONS

A tentative statistical model for lifetime prediction of a parallel-lay aramid rope when subjected to static loads has been developed. It was assumed in its formulation that: a) the lifetime data for ropes of different sizes can be related by normalising the applied stress with respect to the tensile strength; b) the lifetime data of the ropes are best described by a two-parameter Weibull distribution, with the shape and scale parameters being stress dependent; c) the relationship between the characteristic lifetime (scale parameter) and stress level is most conservatively described by an exponential law. The model is based on the above assumptions and on 31 data points, corresponding to stress levels varying from 67.3% to 84.4% of the ultimate tensile strength and times-to-break varying from a few hours to 9 months.



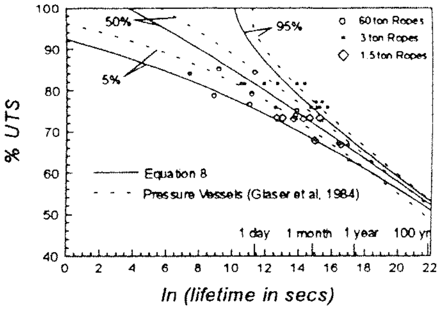


Fig. 1 - Lifetime data for aramid ropes, Kevlar 49 filaments (Wagner et al, 1986), yarns (Howard and Parratt, 1985) and pressure vessels(Glaser et al, 1984)

Fig. 2 - Comparison between lifetime models for aramid ropes (Eq. 8) and Kevlar 49 pressure vessels

It is clear that the experimental data on which the above model is based is still limited and, therefore, its use for estimating lifetimes much larger than the available data (i.e. for low stress levels) should be made with caution. It is believed that an increase in the sample size would not indicate a different functional law for the stress dependence of the scale parameter (Eq. 7) nor would it change significantly the values found for the fitting parameters of expressions [6] and [7].

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