# Jaw effects in yarn testing

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*Key words: Jaw effects, slackness, yarn, clamping device, Kevlar 49*

**ABSTRACT:** One of the major issues in yarn testing for tensile, creep and relaxation effects is the difficulty of clamping of fibres. Two techniques are in common use; the first type fixes the yarn at one point but due to stress concentrations the yarn tends to fail at a low load, so these clamps are not suitable. In the second type the yarn is wrapped around a spindle and then secured at a grip. The full load is not transferred to the grip, but is spreads over the perimeter of the spindle; this results in failure within the testing length. However, this method leads to other problems; the initial slackness and the lack of a well-defined point of load transfer, mean that the effective gauge length is not the same as the nominal gauge length. This is known as the 'jaw effect'.

In this study, tensile tests for Kevlar 49 yarns at various temperatures (25$^{o}$C to 160$^{o}$C) and nominal lengths (350, 250 and 150 mm) were carried out. Three different methods (2 graphical and 1 analytical) were used to determine the initial slackness and the jaw effect. The results show a very good agreement between the three methods; it is shown that a single value for initial slackness and jaw effect can be used that is temperature and length independent.

## INTRODUCTION

In the last twenty years, composite materials, such as carbon, glass and aramid fibres, have been considered for use in concrete structures. These fibres have become increasingly popular in many structural applications due to their unique mechanical properties. They possess a combination of high strength, high stiffness, good resistance to corrosion; they are also lightweight and easy to handle (Burgoyne, 1992). At the present time these materials are several times more expensive than steel, but their unique properties can compensate for the additional first cost if whole life costing is considered (Balafas et al., 2003).

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These fibres can be used as the core material in rope construction. The ropes are made using bare yarns and can be assembled in braided, twisted or parallel-lay forms. These ropes can be used as prestressing tendons in prestressed concrete, as stay cables in bridges and as ropes in the marine industry. The purpose of the current research is mainly focused on using these materials as prestressed tendons.

Fibre reinforced polymers can be tested in the lab as filaments, yarns or ropes. However, most testing, and especially research on the strength, creep, and creep-rupture behaviour of FRPs has been derived from testing on yarns. Filaments need special procedures because they are extremely difficult to handle. Tests on ropes are limited due to the high cost of the required experimental set-up.

Tensile testing requires a clamping device at each end; failure should take place within the testing length and not within the clamp. Two types are in common use. In the first the yarn is fixed at one point in the clamps; this causes stress concentrations to develop at the point of fixity so the yarn tends to fail at or near this point at a low load. Lechat et al. (2008) introduced a pad of yarns to spread the stresses and prevent the failure within the clamp. She successfully avoided premature failure within the clamps when testing polyester yarns (Fig. 1a).

In the second type of clamp the yarn is wrapped each around a spindle and then fixed at a grip. The main advantage is that the full load in not transferred at one point, but is spread over the perimeter of the spindle; this results in failure within the testing length. This arrangement was developed by Alwis (2003) (Fig. 2b) who successfully tested Kevlar 49 specimens. However, it leads to other problems; the initial slackness of the yarn and the lack of a well-defined point of load transfer result in an effective gauge length that is not the same as the nominal gauge length; this is known as the 'jaw effect'.

This paper describes tensile tests have been carried out on Kevlar 49 yarns at various temperatures and nominal gauge lengths using the second type of clamps with a spindle arrangement. It shows how three different techniques can be used to determine the jaw effect at different temperatures and gauge lengths.

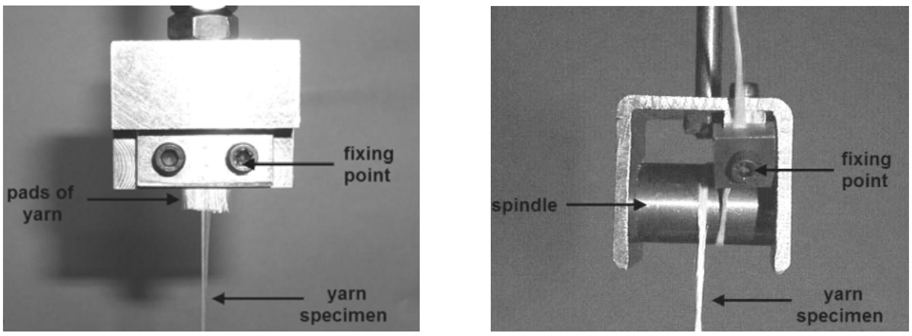



**Figure 1** Clamping device developed by (a) Lechat et al. (2008) and (b) Alwis (2003)

## MATERIAL AND EXPERIMENTAL SET-UP

### Material

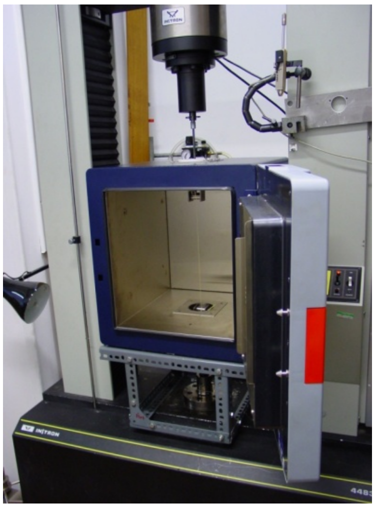
Kevlar 49 yarns, available in reel form, were used for all tests. The reels were kept before testing at constant room temperature (25$^{o}$C) and humidity (50% relative humidity) placed in a black polyester bag inside a box to protect them from ultra violet light, which can affect the properties of the material. The cross sectional area (A) of the yarns, after removing moisture, was found to be 0.17497 mm$^2$. The breaking load was determined by testing twenty different specimens and found to be 444.6 N with a standard deviation of 8.22 N, which is in agreement with the manufacturer's data (Du Pont, 1991).

### Experimental set-up

Tensile tests for determining load vs. elongation and stress vs. strain curves for various test lengths at different temperatures were conducted. The yarn was clamped at both ends by wrapping it around a spindle. The two clamps were fixed to an Instron machine by means of two Invar bars. The bottom clamp was kept stationary and the upper clamp was fixed to the movable cross-head of the testing machine through a 1 kN capacity load cell. Tests had to be carried out at various temperatures levels and for that reason the test apparatus included a Thermo center oven (Fig. 2). The end fittings passed through holes in the top and bottom of the oven that were loosely sealed by PTFE blocks; the two clamps and the yarn were fully inside the oven. The load was applied by moving the cross-head of the testing machine at a constant rate and was measured by a load cell. The cross-head movement was measured by a displacement transducer. The load cell, the displacement transducer and the thermo - couple were connected to a data logger and readings were taken at small time intervals, usually every minute.

For the present study, the second type of clamps was used. However, some minor modifications were made to improve the efficiency. In Alwis' clamps the grip was welded at the right hand side of the jaw. As a result, an eccentricity was induced between the axis of the applied load and the grip, which introduced slippage of the yarn into the spindle during the tests that may have affected the accuracy of the results. In the present study the fixing point was made concentric with the machine axis (Fig. 3); therefore the application of purely axial force is guaranteed.

A mechanical strain gauge was used in the tensile tests to measure the strain of the yarn (Fig. 4). The mechanical strain gauge was made of spring steel. PTFE coated wires and high temperature electrical strain gauges were used so that it could be used with accuracy up to 205$^{o}$C. Before testing, the mechanical strain gauge had to be calibrated at various temperatures.



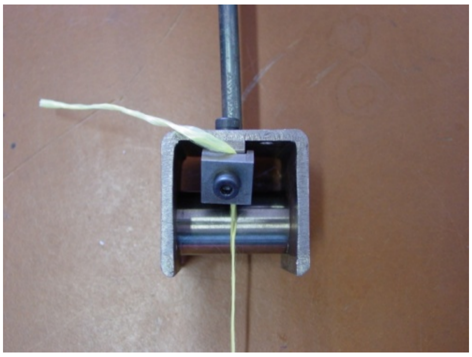


**Figure 2** Testing machine **Figure 3** Clamping device used in the present study

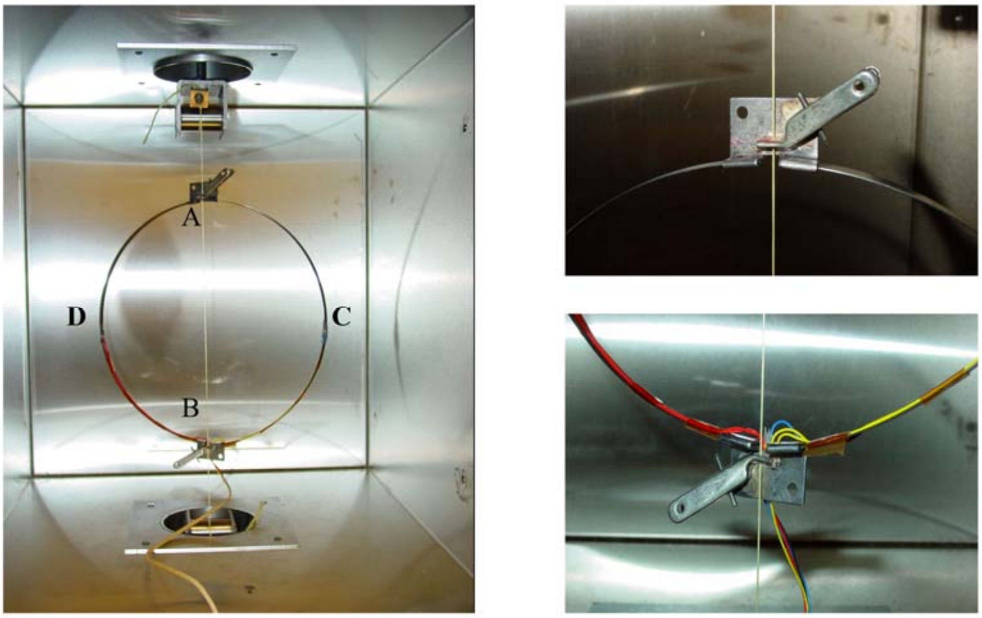



**Figure 4** Mechanical strain gauge mounted on the yarn specimen

## TENSILE TESTS

Tensile tests were carried out as described above at various temperatures. The yarn was wrapped around a spindle and fixed to the grip on the clamp. The mechanical strain gauge was attached to the yarn by the small holding grips available on the metal plates A and B (Fig. 4) which allowed no slip; the length AB was set to 200 mm. For the initial tests, the distance between the tangent point on the spindles (the nominal gauge length) was set to 350 mm. The strain gauge was attached in the central part of the specimen away from the ends and therefore it was not influenced by any jaw effect. When the mechanical strain gauge was attached on the yarn inside the oven, it caused slackness in the yarn due to its weight (1 N). This slackness was eliminated by applying to the yarn a small load of 10 N (2.2% of Average Breaking Load) and initialising the gauge to zero voltage (strain). The oven door was closed and the desired temperature was applied. The top end of the specimen was moved upwards by the Instron machine at a rate of 3 mm per minute until failure of the yarn. During testing readings of the strain and the applied load, monitored by a load cell, were recorded by a data logger. These were used to plot the stress vs. strain curve of the yarn specimen. Three such curves are shown in Fig. 5 for a 350 mm long yarn specimen at 25°C.

This procedure was followed for three yarn specimens at each temperature level: 25, 40, 60, 80, 100, 120, 140, 160°C. The average stress vs. strain curves are shown together for comparison in Fig. 6 and an increase in elongation is observed with increasing temperatures.

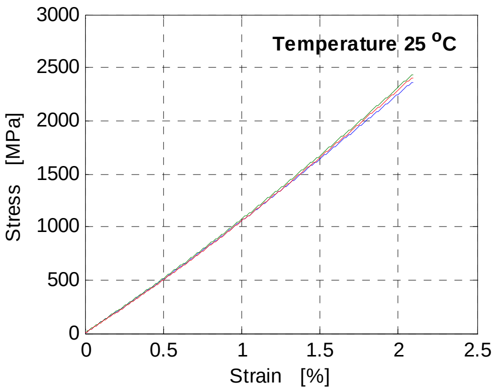



**Figure 5** Stress vs. strain curve using a mech. strain gauge at 25°C

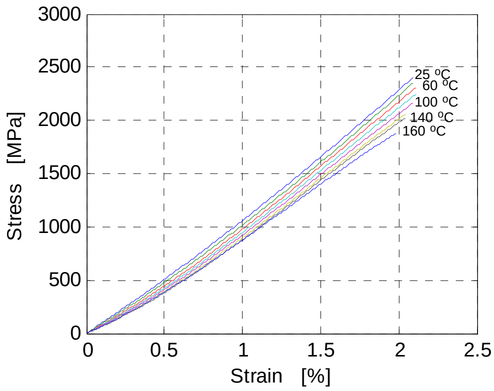



**Figure 6** Average stress vs. strain curve using a mech. strain gauge at all temperatures

## Adjustment for Jaw Effect

In normal yarn testing it is not practical to attach a strain gauge to each specimen, so it is necessary to determine the adjustment that must be made for the jaw effects. In routine tensile testing the specimen is wrapped at each end around the spindle of the jaw and fixed to a point M and M' (Fig. 7(a)). The overall extension is measured by a displacement transducer attached to the top cross-head, while the tensile load is measured by a load cell. The cross-head movement is the same as the extension of the fixed points M and M'.

Tensile tests were carried out on yarn specimens for three test lengths of 150, 250 and 350 mm at temperature levels of 25, 40, 60, 80, 100, 120, 140 and 160°C. Each test was repeated three times, giving a total of 72 tests. All individual tests are presented elsewhere (Giannopoulos et al., 2009b). Typical load vs. elongation curves are given in Fig. 8, which includes the results of nine tests (three tests at each test length) at one temperature level.

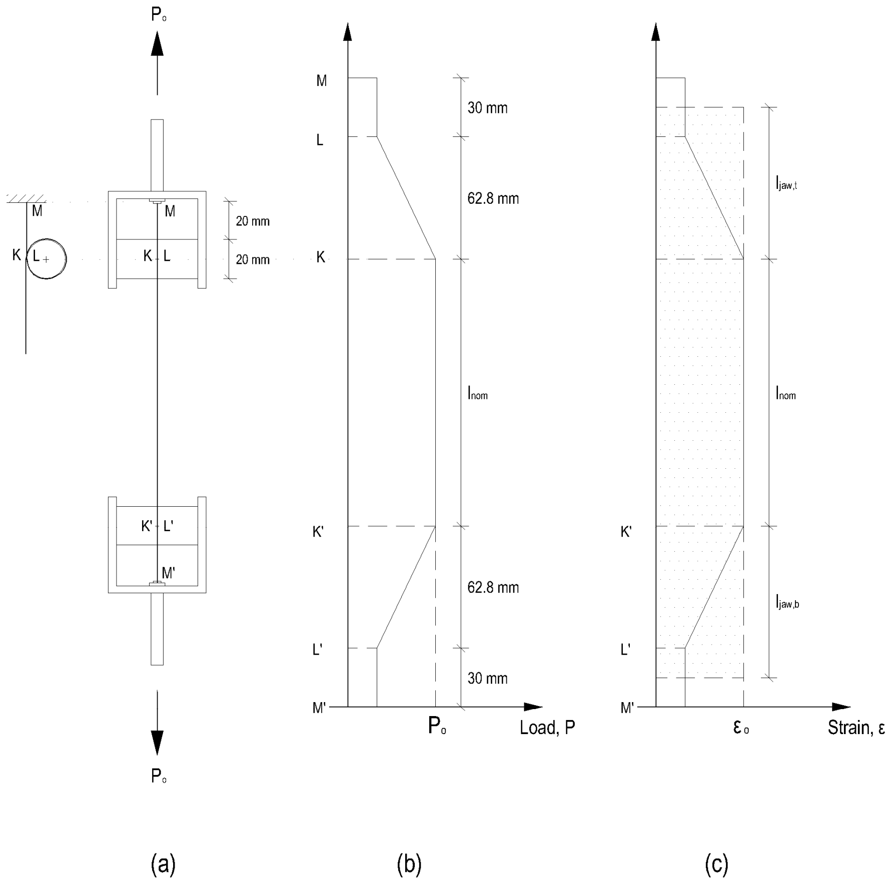



**Figure 7** Yarn wrapped around spindles in the jaws and load and strain distribution along the whole specimen length

All the load vs. elongation curves are characterized by an initially lower stiffness which is caused by slack in the yarn. For a linear material the amount of initial slack ($s$) can be determined by drawing a tangent to the load vs. elongation curve. But for Kevlar 49 yarn this cannot be done since the material is non-linear (Alwis et al., 2008; Giannopoulos, 2009; Giannopoulos et al., 2009a).

The yarn specimen extends between the fixed points M and M' (Fig. 7) attached to the machine cross heads. This test length MM' consists of three parts:

- The central free length KK' between the two clamps, called the nominal length $l_{nom}$.
- The wrapping lengths KL and K'L' along the perimeter of the spindle in each clamp.
- The end free lengths LM and L'M'.

The load along the nominal length is equal to the applied load $P_o$, but it reduces along KL and K'L' due to friction between the yarn and the metal spindle, and it remains constant along the free length LM and L'M'. A typical distribution of load and strain along the whole specimen length is given in Fig. 7 (b) and (c).

The elongation of the overall length MM' of the specimen is equal to the initial slack *s* and the integral of the strains along this length, which could only be computed if the strain distribution was known.

$$\Delta l = s + \int_{M'}^{M} \varepsilon dx \qquad (1)$$

Alternatively, the elongation can be regarded as the extension of an effective length $l_{eff}$ (Fig. 7 (c)) with constant strain ($\varepsilon_o$), which is the strain along the nominal length:

$$\Delta l = s + \varepsilon_o l_{eff} \quad \text{where} \quad \varepsilon_o = P_o/(AE_{sec}) \qquad (2)$$

This effective length comprises the nominal length $l_{nom}$ plus some additional unknown length called the jaw effect

$$l_{eff} = l_{nom} + l_{jaw} \quad \text{where} \quad l_{jaw} = l_{jaw,top} + l_{jaw,bot} \qquad (3)$$

Therefore

$$\Delta l = s + \frac{P}{A\,E_{sec}}(l_{nom} + l_{jaw}) \qquad (4)$$

The strain ($\varepsilon_o = (\Delta l\text{-}s)/l_{eff}$) can thus be computed from the elongation $\Delta l$ provided that the initial slack s and the $l_{eff}$, or the jaw effect, have been determined. This can be done by three different methods:

a) Graphical method using load vs. elongation curves
b) Graphical method using elongation vs. nominal length curves
c) Analytical method

Although the above methods are general in nature, the particular values of the jaw effect and slack apply only to this particular material of the specimen, the testing machine and the jaws used for the tests.

In all methods, it is assumed that the effects of the two jaws are independent. The behaviour in one jaw is not affected by the distance between the jaws, so the difference between two tests of different lengths is only due to the different amount of material between the jaws.

## Graphical method for determining the jaw effect using load vs. elongation curves

In this method the load vs. elongation curves of yarn specimens with different nominal lengths (Fig. 8) are used. The difference between curves obtained for different nominal lengths must only be due to the extra material in the longer test and not to any effects in the jaws. For example, the horizontal distance 'a' between the curves from specimens with a 150 mm and 250 mm nominal length, represents the elongation $\Delta l_{100}$ of 100 mm of yarn. The extension in the jaws, which should be the same in both curves, is eliminated by subtracting the two elongations. The true elongation of a 150 mm long specimen is thus 1.5a. Therefore, by subtracting 1.5a from the elongation of the 150 mm long specimen (point A) point C is obtained; the distance DC represents the elongation in the jaws ($\Delta l_{jaw}$) at this load level.

This process is repeated for various load levels (50, 100, 150, 200, 250 and 300 N). If the variation of strain through the jaws (as shown in Fig. 8) varies linearly as the load increases (which ought to be the case if Coulomb's friction applies) the ratio of DC/AB=$\Delta l_{jaw}/\Delta l_{100}$ should be constant. This means that the plot of elongation in the jaws $\Delta l_{jaw}$ vs. elongation of a 100 mm long specimen $\Delta l_{100}$ (=a) should fit on a straight line (Fig. 9). The fitted line should ideally pass through the origin, because for a zero elongation value the elongation in the jaws should be zero as well. Finally, the slope of the fitted line is equal to jaw effect/100:

$$\frac{\Delta l_{jaw}}{\Delta l_{100}} = \frac{\varepsilon \times l_{jaw}}{\varepsilon \times l_{100}} = \frac{l_{jaw}}{100} \tag{5}$$

The method has been applied for all temperatures levels (25, 40, 60, 80, 100, 120, 140 and 160°C). The method could be also applied to other sets of load vs. elongation curves corresponding to different nominal lengths (e.g. 250 mm and 350 mm). The advantage of using this method is that it is simple; the jaw effects derived (101.6 – 167.1 mm) are not temperature independent.

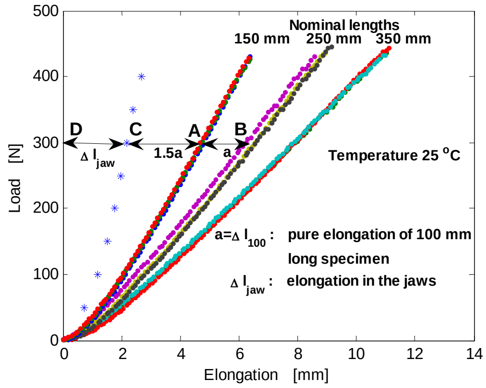



**Figure 8** Load vs. elongation curves used in graphical method

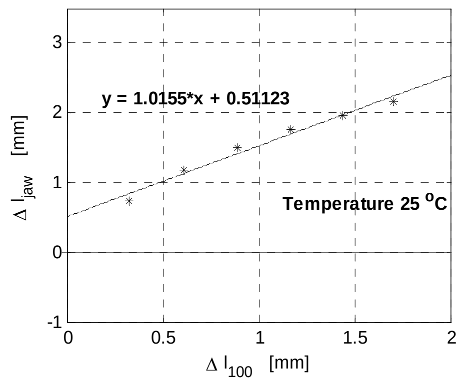



**Figure 9** Elongation in the jaws of 100 mm long specimen ($\Delta l_{100}$) for 25°C

## Graphical method for determining the initial slackness and the jaw effect using elongation vs. nominal length curves

In this method, it is noted that the measured extension includes the extension in the jaws. By extrapolating back to nominally negative gauge lengths, the magnitude of this effect can be determined since there should be some length where there is no extension. Figure 10 shows a graph of elongation $\Delta l$ vs. nominal length $l_{nom}$ for different load levels P. If the jaw effect is independent of the load, the fitted lines should meet at a point I. The distance OO' represents the initial slackness and the distance O'I represents the jaw effect $l_{jaw}$.

This method was applied by Merii (1992), who tested Kevlar 49 yarns and showed a rather large scatter of the lines about the meeting point. A rather larger number of tests (twenty tests at each of five different nominal lengths) by Amaniampong (1992) on Kevlar 49 yarns showed a very good convergence to a single meeting point giving a mean jaw effect of 109.4 mm (using different clamps).

From the tensile tests carried out in the present study, the resulting load vs. elongation curves were used to plot the specimen elongation $\Delta l$ (cross-head movement of the machine) vs. nominal lengths $l_{nom}$ under different load levels P for each temperature level. Lines were fitted to the data and extended to meet at a point I giving the jaw effect and the initial slackness. The plot at 25°C is given in Fig. 11. The fitted lines do not meet in a single point but in a small region, where the initial slackness and the jaw effect are determined with an accuracy that is satisfactory taking into account the inherent scatter in the material properties of the yarn. The results for all test lengths and all temperatures are given together in Fig. 12 and a mean initial slackness of 0.50 mm and mean jaw effect of 140.6 mm are derived.

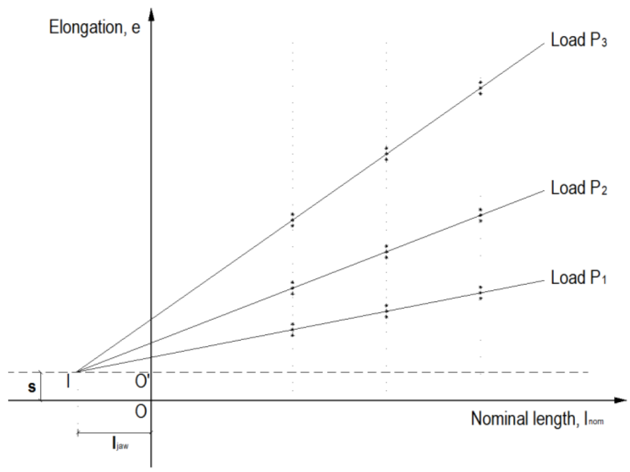



**Figure 10** Graphical determination of initial slackness and jaw effect from fitted lines to elongation vs. test length data for different load levels

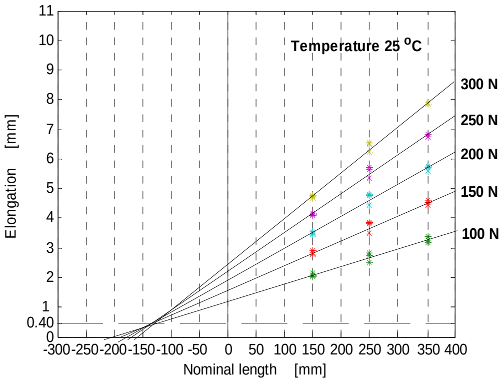



**Figure 11** Elongation vs. test length data for 25°C

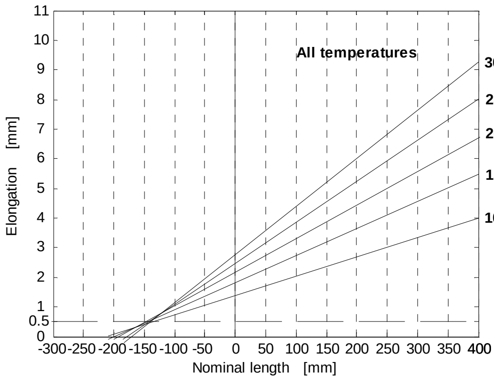



**Figure 12** Elongation vs. test length data for all temperatures

## Analytical method for determining the initial slackness and the jaw effect

This method assumes that the extension can be determined using equation 4, to which an extra term $a_i$ is added to represent the error. This gives:

$$\Delta l_i = s + \frac{P_i}{A\,E_{sec,i}}(l_{nom} + l_{jaw}) + a_i \tag{6}$$

The unknowns now are the the initial slack (s) and the jaw effect ($l_{jaw}$); the load ($P_i$) and elongation ($\Delta l_i$) are measured and the secant modulus $E_{sec,i}$ can be determined from the stress vs. strain curves using a mechanical strain gauge. More details can be found elsewhere (Giannopoulos, 2009). The cross-sectional area (A) and the nominal length ($l_{nom}$) are known. The unknowns are found iteratively by minimizing the Sum of Squared Errors using Matlab.

The detailed results of the iteration process for the 3 nominal lengths and 8 temperature levels for the Kevlar 49 yarn are given elsewhere (Giannopoulos, 2009). From the results a small scatter is observed, giving for the jaw effect a mean value of 140.0 mm (70 mm for each end) for all test lengths and all temperatures. The initial slack has a mean value of 0.42 mm and it shows a larger scatter than the jaw effect. This value of the slack depends a lot on the handling of the fixity of the specimen ends. The validity of adopting a single value for the jaw effect and the initial slackness for all test lengths and temperatures is discussed below.

## Determination of stress vs. strain curves from load vs. elongation curves

Once the jaw effect and slack are known, it is trivial to use these and equation 4 to get the stress-strain curves. This can be done in two ways; firstly using the analytically determined values for each test separately, and secondly using an average value for all tests.

An example of the first method is shown in Fig. 13, which shows the results for nine tests (using three different gauge lengths) at 25°C. Also shown, as a dotted line, is the data obtained using the strain gauge (from Fig. 5); there is clearly very good agreement, which validates the method used. Additionally the small scatter observed in the load vs. elongation curves for test repetitions (Fig. 5) diminishes practically to zero in the corresponding stress vs. strain curves (Fig. 13) derived by introducing the individual initial slackness and the jaw effect into each curve.

Figure 14 shows the same data, this time using the mean jaw effect ($l_{jaw}$ = 140.0 mm) and slack (s = 0.42 mm). As would be expected, the agreement is not as close, but it is sufficiently good for most practical purposes. A very small scatter (± 0.8 to ± 1.4 %) around the mean curve obtained using the mechanical strain gauge is observed.

Therefore taking into account the inherent scatter in the material properties it can be concluded that the initial slackness and the jaw effect are practically length and temperature independent. A single value can be used which, for this material (Kevlar 49) and this machine with its jaws, is s = 0.42 mm and $l_{jaw}$ = 140.0 mm.

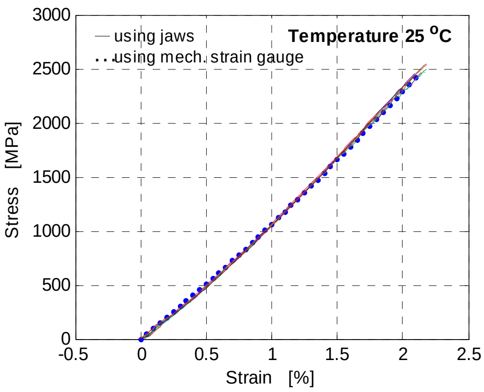



**Figure 13** Stress vs. strain curves using individual values for s and $l_{jaw}$ at 25°C

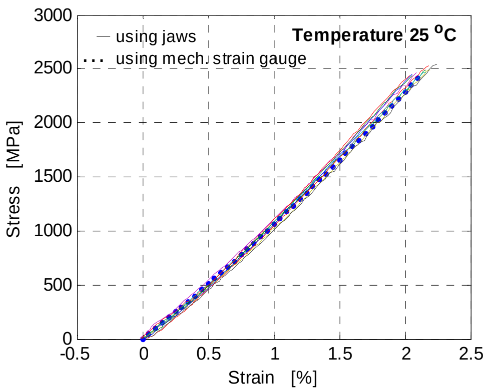



**Figure 14** Stress vs. strain curves using mean values for s and $l_{jaw}$ at 25°C

## CONCLUSIONS

Three different methods (2 graphical and 1 analytical) for determining the initial slackness and the jaw effect were successfully applied on available tensile data on Kevlar 49 yarns at three different gauge lengths (350, 250 and 150 mm) at various temperatures (25 to 160$^o$C). The two graphical methods are quick and easy to apply but only give a rough estimation of the jaw effect. A more rigorous calculation of the jaw effect is done using the analytical approach, but this method is more complex and requires computer iteration. The results have shown good agreement for the three methods; a single value for initial slackness and jaw effect can be used, which is temperature and length independent. The values only apply to the particular set of jaws used here but the techniques are general in nature and can be applied to any similar testing arrangement and any similar material.

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