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The strength of spider silk

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Tensile tests have been made on the draglines of the Queensland Bird-Catching Spider (*Nephila maculata*): the masses of the several spiders varied by a factor of about 25. The nominal fracture strength of the silk was independent of the spider size and was about 1100 MPa (the true fracture strength was about 1500 MPa). Larger spiders extruded proportionately thicker draglines and the maximum force which a dragline could sustain was generally two or three times the body weight of the spider. Draglines consisted of two or four individual threads and some tests were made of the properties of these constituent strands. Tests made on draglines aged for 21 days showed only a moderate deterioration in properties although a marked change occurred in the initial part of the stress–strain curve.

1. Introduction

Although it is widely believed that spider's silk is "very strong" it is remarkable how few determinations of its strength have been made. An early experiment was that of Benton [1] who measured a strength of 180 MPa and an elongation of 20%. Professor C. E. Inglis is reported to have measured a strength of about 1100 MPa in 1932 but details of the experiment were not given in the newspaper which carried the story.† More recently, Lucas [2] made isolated tests on the silk of *Araneus diadematus* and reported a true strength of about 1200 MPa for the dragline. In a more comprehensive study Denny [3] obtained single fibres of dragline from several webs of *Araneus sericatus* and found true fracture strengths between 800 and 1400 MPa. Denny found a large variation in specimens from different webs, but he was unable to determine whether or not some of his spiders produced stronger silk. Work [4] also cut single fibres of dragline from the webs of *Argiope aurantia, A. argentata, Araneus diadematus* and *Euriophora fuligenia*. He found true fracture strengths of about 1800 MPa with fracture strains varying from 26 to 42%. Work noted that dragline consists of a pair of larger fibres (extruded from the major ampullate glands) and a pair of thinner fibres (from the minor ampullate glands): he suggested that the smaller fibres have much lower strengths (by a factor of nearly two) although they had similar fracture strains.

In this paper we describe the results of tensile tests of the dragline of the Queensland Bird-Catching spider, *Nephila maculata*. This spider was chosen since her webs are particularly famous for their size and strength – indeed they have been used by the inhabitants of several of the Pacific Islands as fishing snares and also, in the New Hebrides, as masks to smother the guilty party in adultery cases [5]. The tests were designed to discover whether the tensile properties of the dragline of any one spider vary from day to day and, also, whether significant variations exist between the draglines of different individuals.

2. Experimental procedure

2.1. Specimen preparation

Three *Nephila maculata* of very different sizes were provided by the Kamerunga Biological Laboratories at Cairns, Northern Queensland. Experiments were done within 2 or 3 days of the spiders' arrival although one specimen was kept for a month and five separate determinations made of the strength of her dragline. The procedure for obtaining

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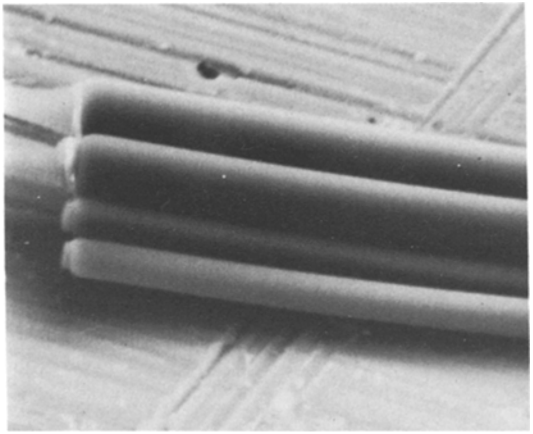

Figure 1 Scanning electron micrograph of dragline (× 1000). In this example inadequate gold deposition has resulted in the electron beam fusing the fibres.

tensile test samples was to let the spider walk along the laboratory bench leaving a dragline: the walking speed of the two smaller spiders varied between 30 and 55 mm sec^{-1}: the largest spider walked at about 12 mm sec^{-1}. After the spider had walked about a metre, adhesive tape was fixed along the line to make a series of tensile samples, each 100 mm long. The adhesive tapes, when folded onto themselves, made convenient grips for the tensile specimens. Short segments, about 10 mm long, between the tensile specimens were isolated for measurements of diameter (see Section 2.3). Tensile tests were done within 3 h of this procedure, although a few tests were also made with dragline that was left taped to the bench for 3 weeks. Other methods for obtaining dragline were tried. These included letting the spider fall from a bench and using the resulting dragline, or winding dragline off on a rotating cylinder. However, such methods generally produced material with unacceptably variable properties.

The dragline consisted of two to four separate threads (Fig. 1) and these threads were readily separable so that tensile tests could be made with single strands.

2.2. Tensile tests

The specimens were tested in an Instron machine with a constant cross-head speed of 20 mm min^{-1}, corresponding to a strain rate of 3×10^{-2} sec^{-1}. No control was made over room temperature (which varied from 23 to 27° C during this programme) or humidity.

2.3. Measurements of diameter

The short segments of dragline between the tensile samples were stuck on an aluminium disc, coated with gold by vapour deposition, and examined in a Cambridge S4-10 scanning electron microscope at 10 kV. Photographs (Fig. 1) were taken of each segment and the mean diameter from successive segments was taken as being representative of the intervening tensile specimen (the thickness of the gold coating was negligible compared with the diameter of the threads).

3. Results and discussion

3.1. The tensile strength

The general form of the force–extension curves is shown in Fig. 2. The scanning microscopy confirmed what is suggested by the force–extension curves – that the dragline consisted of several, usually four, separate threads, two thick and two thin (Fig. 1). For the smallest spider, four threads were only occasionally seen: the usual number was two. Three threads were never seen. Measure-

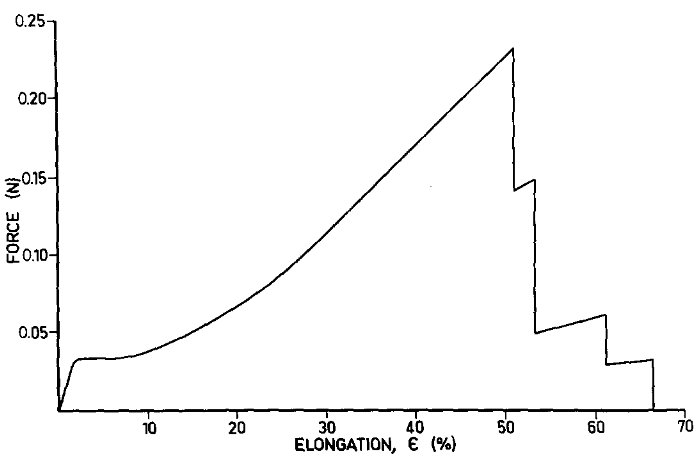

Figure 2 Typical force–extension curve for fresh dragline (experiment C1).

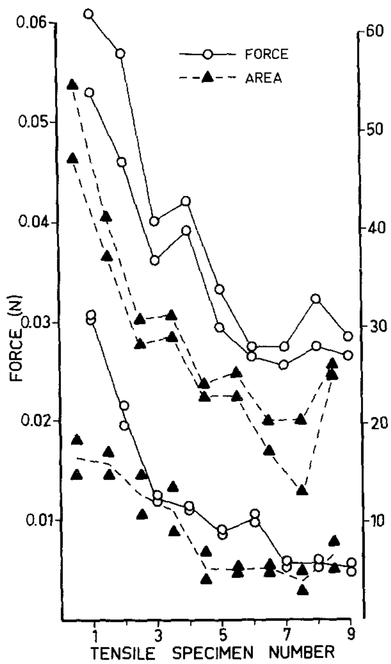

Figure 3 Tensile strengths and fibre cross-sectional areas of specimens cut from one dragline (experiment B4).

ments were made of the individual load drops and an example of how these varied along one typical dragline is shown in Fig. 3. Also plotted in Fig. 3 are the measurements of the fibre cross-sectional area: in some cases measurements on all the fibres in any one segment could not be made because they were obscured.

The most obvious fact about Fig. 3 is that the dragline is tapered, being thicker at the start. Tensile stresses were calculated by dividing each load drop by the appropriate area – making the natural assumption that the thicker threads carried the higher loads. The tensile strength can be expressed as the *nominal strength* (the maximum load divided by the original cross-sectional area) or as the *true strength* (the maximum load divided by the cross-sectional area of the stretched fibre). If it is assumed that extension occurs with no change of volume of the fibre then the true strength is found by multiplying the nominal strength by $(1 + \epsilon)$ where ϵ is the elongation (the ratio of the ultimate length of the specimen to its original length is $1 + \epsilon$). An an example, the true tensile strengths calculated from the data in Fig. 3 are shown in Fig. 4 and it can be seen that they are sensibly constant.

The means and standard deviations of the data from all the experiments are summarized in Table I. The letters A, B, and C refer to the three spiders used. The strength data in Table I are only for the thicker pair of fibres in the dragline since, although we could not detect a significant difference between the thicker and thinner pair, the scatter in the latter data was larger because of difficulties in diameter measurements. Furthermore, we could not distinguish between strengths calculated from experiments on complete draglines and those made on individual threads tested separately. The five experiments with specimen B were done over 36 days and the body weight data show that she did not eat well in captivity; she responded by spinning thinner dragline (reflected in a lower load-carrying capacity) although its tensile strength was unaffected.

Table I shows that the tensile strength is essentially constant, irrespective of the mass or health of the spider, and has a value of about 1100 MPa (nominal stress) or 1500 MPa (true stress). This value is consistent with the previous data [2–4] and extends them insofar as the relationships between strength and spider mass are concerned. However, our data do not support the suggestion [4] that the thinner fibres in the dragline are much weaker than the thicker ones:

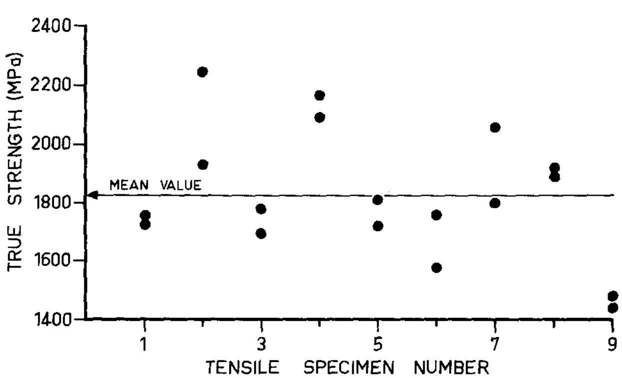

Figure 4 True strengths calculated from Fig. 3 (thicker pair of fibres only).

TABLE I Details of the tensile tests

Experiment no.	A1	A2	B1	B2	B3	B4	B5	C1
Date	5 Dec	10 Dec	4 Dec	5 Dec	8 Dec	10 Dec	7 Jan	16 Jan
Spider weight (N)	0.0045	0.0038	0.037	0.035	0.034	0.034	0.029	0.099
Number of tests	5	8	6	4	3	8	5	4
Range of maximum force sustained by complete dragline (N)	0.027–0.013	0.027–0.013	0.142–0.109	0.156–0.104	0.129–0.098	0.162–0.061	0.075–0.038	0.329–0.158
Nominal fracture strength (MPa)	1060 ± 70	1190 ± 150	1100 ± 110	1230 ± 210	960 ± 70	1360 ± 160	980 ± 80	1090 ± 90
True fracture strength (MPa)	1550 ± 100	1600 ± 230	1470 ± 200	1630 ± 310	1250 ± 110	1850 ± 230	1290 ± 120	1680 ± 150
Elongation of thicker pair of threads (%)	44 ± 6	33 ± 4	34 ± 3	30 ± 3	29 ± 3	34 ± 4	31 ± 2	52 ± 4
Elongation of thinner pair of threads (%)	67 ± 12		42 ± 3	39 ± 4	39 ± 3	43 ± 6	41 ± 3	64 ± 5

on the contrary; we could not detect a significant difference in their strengths. Furthermore, the "safety factor" in strength (the ratio between the spider's mass and the dragline strength) of between 2 and 3 as shown in Table I is rather higher than the value of about 1.5 given by Lucas [2].

These data amply vindicate the reputation for strength enjoyed by spider's silk. Indeed it is only just bettered by the best modern polymer fibres, an example being Kevlar [6, 7] which can have a strength of 1650 MPa.

3.2. The elongation

The force–extension curves (Fig. 2 and Table I) suggest that the thinner pair of fibres can withstand a much greater extension than can the thicker pair. However, the tests done with the separate threads showed that the different threads probably have similar properties. The data are summarized in Table II.

The behaviour of the complete dragline is consistent with the idea that the thicker threads are extruded under some tension so as to leave the thinner ones effectively slack, but this phenomenon has not been tested further. The effect of the phenomenon is that the load is mostly borne by the thicker threads, whilst the thinner ones are in reserve, perhaps for safety purposes. Table II also shows that the dragline from the heaviest spider C, was much more extensible than that from B. In the absence of data from more specimens, however, we do not consider this observation significant: for example, the dragline from A was also more extensible than that from B (see Table I).

3.3. Ageing effects

Some specimens of the dragline from spider C were left taped to the bench for 21 days before testing. The data are given in Table III and show that the properties of the silk deteriorated to some extent.

The most noticeable effect was that the aged sample developed a marked yield point, an example being shown in Fig. 5. No further study was made of the phenomenon although it may be significant that one test specimen which was left to age freely hanging (that is, in a condition of constant stress, instead of being taped to the bench in a condition of constant length) did not show the yield drop.

TABLE II The elongation (%), with standard deviations, of the two pairs of threads

Experiment no.	Thicker pair		Thinner pair	
	B3	C1	B3	C1
Tested as a complete dragline	29 ± 3	52 ± 4	39 ± 3	64 ± 5
Tested separately	27 ± 2	46 ± 4	26 ± 4	51 ± 6

TABLE III Effects of ageing on the properties of dragline

	Tested at once	Tested after 21 days
True fracture strength of thicker pair (MPa)	1680 ± 150	1280 ± 240
Elongation of thicker pair (%)	52 ± 4	45 ± 6

4. Conclusions

The following conclusions may be drawn from this work:

(1) The dragline of *Nephila maculata* consists of up to four smooth threads, often arranged as a thicker and thinner pair.

(2) The dragline, at least as laid by a spider walking on a level surface, is tapered with its largest diameter being at the attachment pad.

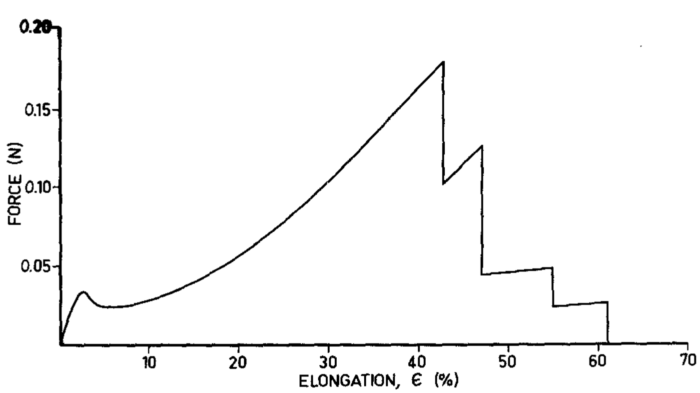

Figure 5 Typical force–extension curve for dragline aged for 21 days.

(3) The room temperature nominal strength of the individual threads making up the dragline is about 1100 MPa: the true strength is about 1500 MPa. This strength was found for the dragline of one spider obtained over a period of a month and for two other spiders and was independent of the weight of the spider and of her state of health.

(4) The fracture strain of the individual dragline threads varies between about 30 and 50%. Although a test on a dragline shows that the thinner threads can apparently sustain much higher strains than the thicker ones, measurements on isolated threads show that the thinner threads are not, in fact, more extensible.

(5) Some preliminary work on the effect of ageing showed that the nature of the yield point could be affected. Effects on the strength and fracture strain were less marked.

Acknowledgements
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