J. exp. Biol. **116**, 141–151 (1985)
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MECHANICAL PROPERTIES AND FACTORS OF SAFETY OF SPIDER DRAG-LINES

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Accepted 10 September 1984

SUMMARY

Experiments were carried out to determine the strain energy capacity and breaking strain of spider drag-line silk. These properties are discussed in terms of a mathematical model of a spider falling on a drag-line. It was found that the strain energy capacity of the drag-line was insufficient to absorb the potential energy lost by a falling spider and that in order to avoid failure of the drag-line the spider dissipates energy by other means, particularly by using its inertia to draw drag-line silk from its spinnerets.

INTRODUCTION

Alexander (1981) argued that if an animal skeleton is too weak it is likely to break in use, but if it is too strong it is cumbersome and costly to produce. Between these two extremes there will be an optimum strength that will be favoured by natural selection. Alexander presented a mathematical model which made predictions about the relationships between the strengths of animal structures and the size and variability of the loads which they are required to sustain. These relationships were discussed in terms of the factor of safety, which is the strength of a structure divided by the maximum load expected to act on it. Most of the published estimates of factors of safety for animal structures, quoted by Alexander lie between 1·3 and 5·0.

This paper presents an attempt to estimate factors of safety for the drag-lines of argiopid spiders. When these spiders are active, they spin a drag-line which is periodically anchored in a similar way to a rock-climber using a safety rope. If the spider falls or is disturbed and jumps from the surface on which it was climbing, its fall is arrested and it is held in the air by the drag-line. Spiders may make controlled descents on the line by spinning more silk or they may return up the line, gathering it into a bundle as they climb (personal observation).

Lucas (1964) hung weights on drag-lines and found they would support about 1·5 times the weight of the spider. However, as he noted, a drag-line halting a falling spider must withstand the inertia forces associated with the spider's deceleration, in addition to the spider's weight. We have to consider the impact strength of the silk,

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Key words: Safety factors, spider drag-lines, spider silk, *Meta segmentata*.

rather than its static strength. Denny (1976) showed that frame silk – which is produced from the same spinnerets as drag-line silk (Lucas, 1964) – tends to deform elastically and fracture with little yield. Therefore the impact strength depends almost entirely on strain energy capacity (Alexander, 1983).

A spider of weight W falling through a height h loses potential energy Wh. A strand of volume V of silk of strain energy capacity C is capable of storing strain energy VC. It will be shown below that for the short falls considered, work done against air drag is negligible. Thus if a spider liable to fall through height h depends on a drag-line of volume V, the quantity VC/Wh can be regarded as the factor of safety.

A spider may be above, below or to one side of the anchorage point of its drag-line. The most dangerous situation for a drag-line of length l_0 occurs when the spider is a height l_0 above the anchorage point. If it falls it loses height $2l_0$ before the drag-line becomes taut. It falls further, stretching the drag-line, before being halted: this further distance may be up to $\epsilon_f \cdot l_0$ where ϵ_f is the strain of the silk at failure. Thus we may take $h = (2+\epsilon_f)l_0$, and $V = Al_0$, where A is the cross-sectional area of the unstressed silk. Thus the factor of safety may be defined as:

$$n = \frac{AC}{(2+\epsilon_f)W} \cdot \qquad (1)$$

Notice that the length of the drag-line does not appear in this expression. The quantity AC is the amount of strain energy which may be absorbed by a unit length of silk. This paper describes experiments designed to measure AC and ϵ_f from drag-line silks of the argiopid spider *Meta segmentata* (Clerck).

METHODS

Principle of experiments and apparatus used

If a weight is attached to a drag-line and allowed to fall, it will lose potential energy, some of which will be converted to kinetic energy and the remainder will be used in stretching the drag-line. If the weight is heavy enough to break the line then the difference between the kinetic and potential energies of the weight after the drag-line has broken will be equal to $AC \cdot l_0$ where AC is the strain energy capacity per unit length of the line and l_0 is its original unstressed length. It is this principle on which the experiments were based.

Experiments were carried out using the apparatus shown in Fig. 1. Drag-line silk was obtained by allowing a spider to walk along a cylindrical polyvinylchloride rod, the surface of which had been roughened with emery paper. When the rod was tapped gently the spider jumped from it and hung below on a drag-line. A length of the drag-line was attached at its upper end to the metal block by means of double-sided adhesive tape and at its lower end it was attached to a strip of single-sided adhesive tape which was fixed between two rigidly mounted metal strips (Fig. 1). A second strip of tape was placed over the lower tape, forming a sandwich of the silk line between the two pieces of tape. The height of the metal block was then adjusted by means of the micromanipulator until the silk was slack. A notch was then cut in the lower tape attachment, leaving a narrow strip of tape holding the silk (Fig. 2A). A fisherman's lead split shot of known mass (which was large enough to break the drag-line) was gently clamped, using forceps, to the tape at the same point at which the drag-line was attached. While the shot was held with forceps, the tape to either side was cut away

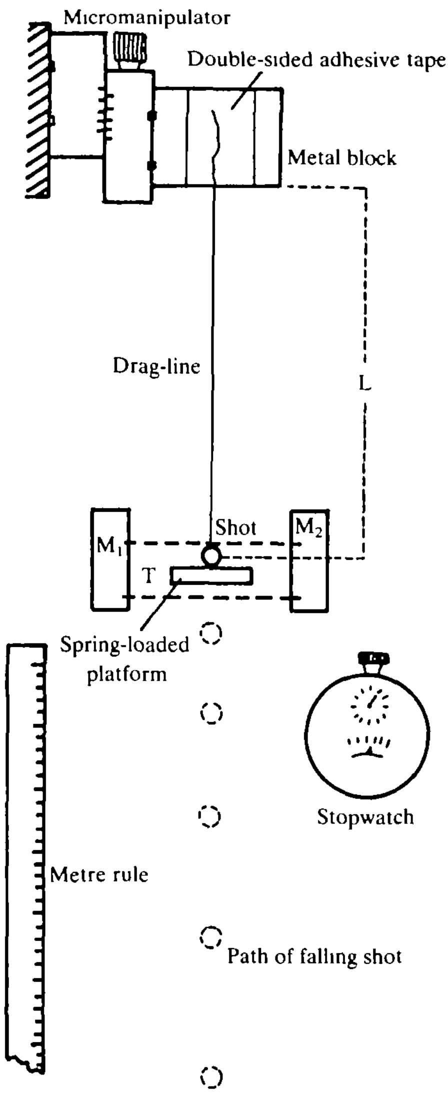

Fig. 1. Diagram of apparatus. The height of the metal block could be adjusted with the micromanipulator. The distance L was measured with the micromanipulator scale set at zero. The starting length, l_o, of the silk was then calculated from the adjusted scale reading. M_1, M_2 are rigidly mounted metal strips used to hold the single-sided adhesive tape, T, to which the lower end of the drag-line was first attached (see text). When released, the spring-loaded platform was withdrawn rapidly to one side, thus allowing the shot to fall.

with a scalpel leaving the end of the silk clamped between the jaws of the shot (Fig. 2B). The lower end of the silk was sandwiched between tape within the jaws of the shot in this way in an attempt to avoid damage to the silk at the point of attachment.

The lead shot with drag-line attached was then placed on the spring-loaded platform (Fig. 1) and the height of the metal block was again adjusted until the drag-line was just slack. The spring-loaded platform was triggered, causing the shot to fall. The falling shot was filmed using a 16 mm ciné camera at a nominal framing rate of 64 frames per second. The actual framing rate was determined from a stopwatch which was placed in the field of view of the camera. In order to minimize parallax errors, filming was carried out from a distance of 1·7 m using a lens of long focal length. The distance the shot had fallen was determined from a vertically mounted metre rule which was also in the field of view, alongside the path of the falling shot.

In order to assess the effects of air drag on falling spiders, the following experiment was performed. Spiders were anaesthetized with carbon dioxide gas and weighed. Each spider was then placed in an upright position on the spring-loaded platform of the apparatus (Fig. 1). The platform was triggered and the falling spider was filmed at a nominal 64 frames per second. Distance fallen and times were obtained from the films as described above.

Spiders were filmed in the laboratory making controlled descents on their drag-lines. Distance of descent and times were obtained from the films.

Although it was not necessary to measure A in order to determine AC, cross-sectional area of unstressed silk was estimated for comparison with values published by other workers. Samples of drag-line from several spiders were examined under a binocular microscope. Each line was found to be composed of two intertwined silk strands. It was assumed (untested) that the strands were circular in cross-section and the total cross-sectional area of the two strands was determined from their diameters.

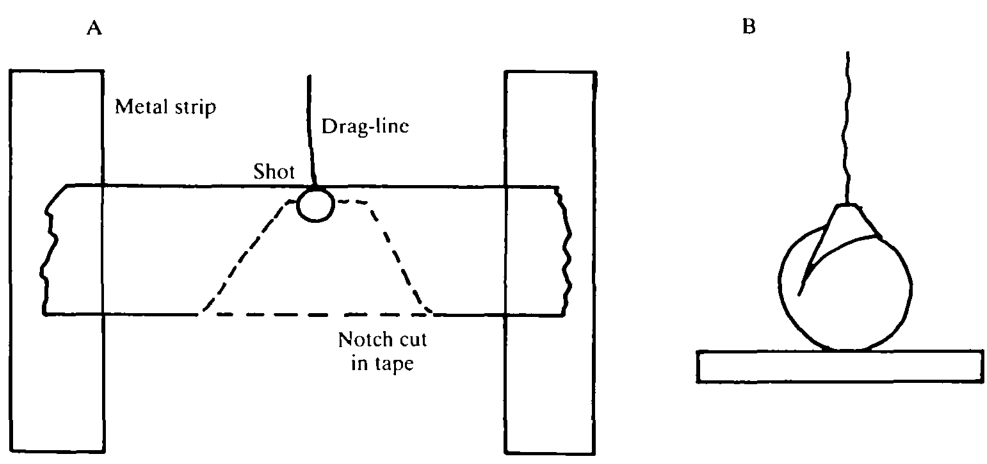

Fig. 2. Method of attachment of lead split shot to the drag-line. (A) Drag-line sandwiched between adhesive tape to which a split shot is attached. (B) The tape is cut away to both sides of the shot, which is placed upon the spring-loaded platform.

Calculations used in analysis

From the values of distance and time obtained from the films, velocities and accelerations were calculated. Small errors in measurement of distance tend to be considerably amplified when velocities and accelerations are derived. Therefore, these calculations were carried out using the smoothing technique described by Lanczos (1964). This technique involved fitting local least-squares parabolae of the form $y = a+bx+cx^2$ through a small number of data points spanning each time value on the distance-time curve. The velocity and acceleration at each time point were calculated from the coefficients b and c.

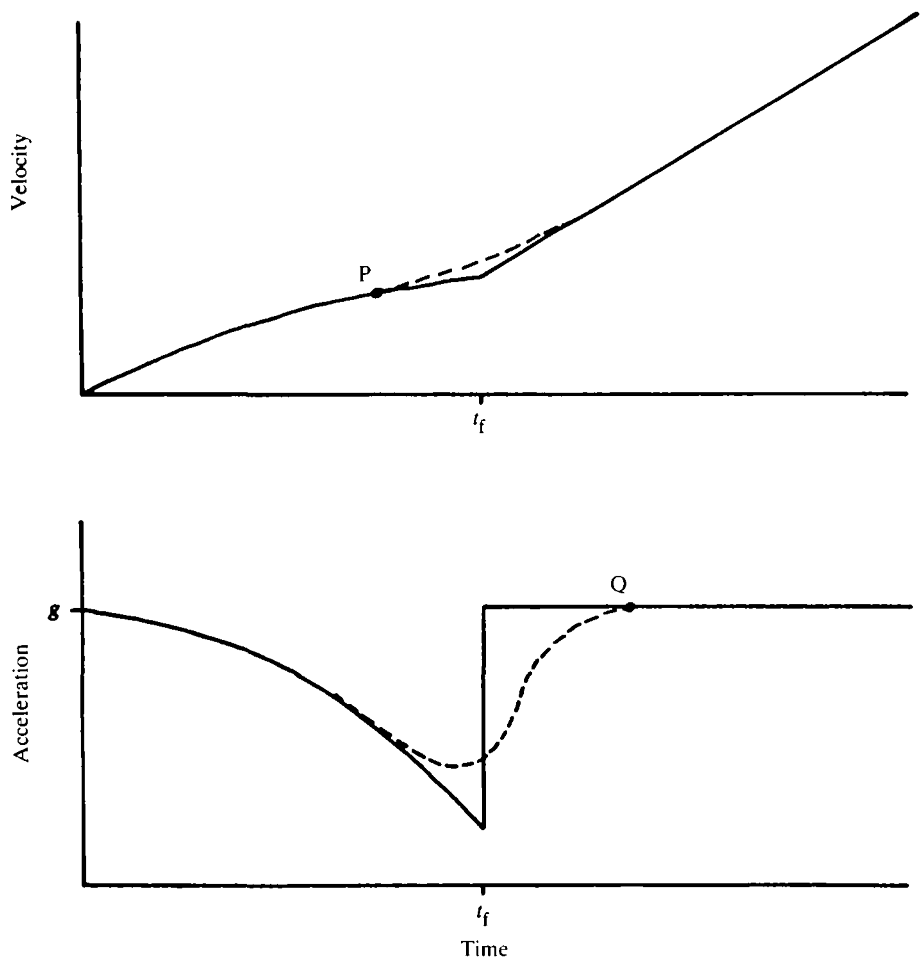

Fig. 3. Schematic diagrams showing true changes (continuous lines) in velocity and acceleration of a shot falling on a drag-line and the curves (broken lines) which are produced by data smoothing. The point of inflection on the smoothed velocity curve and the point Q, at which the smoothed acceleration curve reaches g should be s data points before and after the time of failure of the drag-line, t_f, respectively, where $(2s+1)$ is the number of distance points used to calculate each smoothed velocity or acceleration value (see text). The continuous curves shown are those that would be expected if there were no measurement errors in the distance data. Note that the smoothing technique overestimates velocity at t_f.

Consider the acceleration of a falling shot which is attached to the end of a drag line. Initial downward acceleration would be $\mathbf{g}$, the acceleration due to gravity. It would be expected that the acceleration would decrease as the shot fell, due to the retarding force of the stretching drag-line and then return suddenly to $\mathbf{g}$ as the drag-line failed. However, the smoothing techniques used to reduce the effect of errors in distance measurement also tended to smooth out real sudden changes in velocity and acceleration which were associated with failure of the drag-line. Fig. 3 shows the relationship between smoothed and true values of velocity and acceleration. It can be seen that the values calculated using the smoothing technique deviate from the true values for s data points either side of the time of failure t_f, where $(2s+1)$ is the number of distance points used in calculating each smoothed velocity and acceleration value. Thus the smoothed values for acceleration of the falling shot do not reach $\mathbf{g}$ until s data points after t_f (Fig. 3, Q).

As the shot fell, some of its potential energy was converted to kinetic energy and the remainder was used to stretch and break the silk and also to overcome air resistance. The quantity of lost potential energy (mgh) *not* converted to kinetic energy ($mu^2/2$) at any particular time was calculated from the equation:

$$E_d = mgh - \frac{mu^2}{2}, \tag{2}$$

where m was the mass of the shot, u its velocity and h was the distance which it had fallen.

As the shot fell it experienced a drag force D due to air resistance which is given by the equation:

$$D = l\rho u^2 S C_D, \tag{3}$$

where ρ is the density of air ($1{\cdot}3\,\mathrm{kg\,m^{-3}}$), S is the cross-sectional area of the shot (about $3\times10^{-6}\,\mathrm{m^2}$) and C_D is the coefficient of drag. Shot fell at velocities of up to about $2\,\mathrm{m\,s^{-1}}$. For a spherical object the size of the shot used, C_D is about 1 for velocities between 1 and $3\,\mathrm{m\,s^{-1}}$ (Prandtl & Tietjens, 1957). Thus the drag force on the shot when it was falling at $2\,\mathrm{m\,s^{-1}}$ was about $8\times10^{-6}\,\mathrm{N}$. The average drag force as the shot accelerated from rest to $2\,\mathrm{m\,s^{-1}}$ must have been less than this. The shot had fallen about 0·3 m when it had reached a velocity of $2\,\mathrm{m\,s^{-1}}$. Thus the energy lost due to drag was less than 2·4 μJ. This was less than 0·3 % of the typical total potential energy loss of about 1 mJ for a shot falling (about) 0·3 m and so was neglected. Thus it can be seen that the strain energy stored in the drag-line, E_s is equal essentially to the quantity E_d calculated from equation (2).

It has been shown (Fig. 3) that the smoothing of distance data causes the velocity of fall of the shot to be overestimated at t_f. Hence, from equation (2) it can be seen that E_s will be underestimated at t_f. Nine-point smoothing was used to estimate velocities used to calculate E_s from equation (2) (i.e. velocities were calculated from parabolae fitted through nine consecutive distance data). A typical graph of E_s against time is shown in Fig. 4, along with the corresponding acceleration curve. Once the drag-line had broken, the photographic image of the shot soon became blurred due to its rapidly increasing velocity which increased the errors in distance measurement. In order to avoid errors caused by the underestimation of E_s due to data smoothing and also to minimize random errors because of the blurring of the image of the shot, the strain

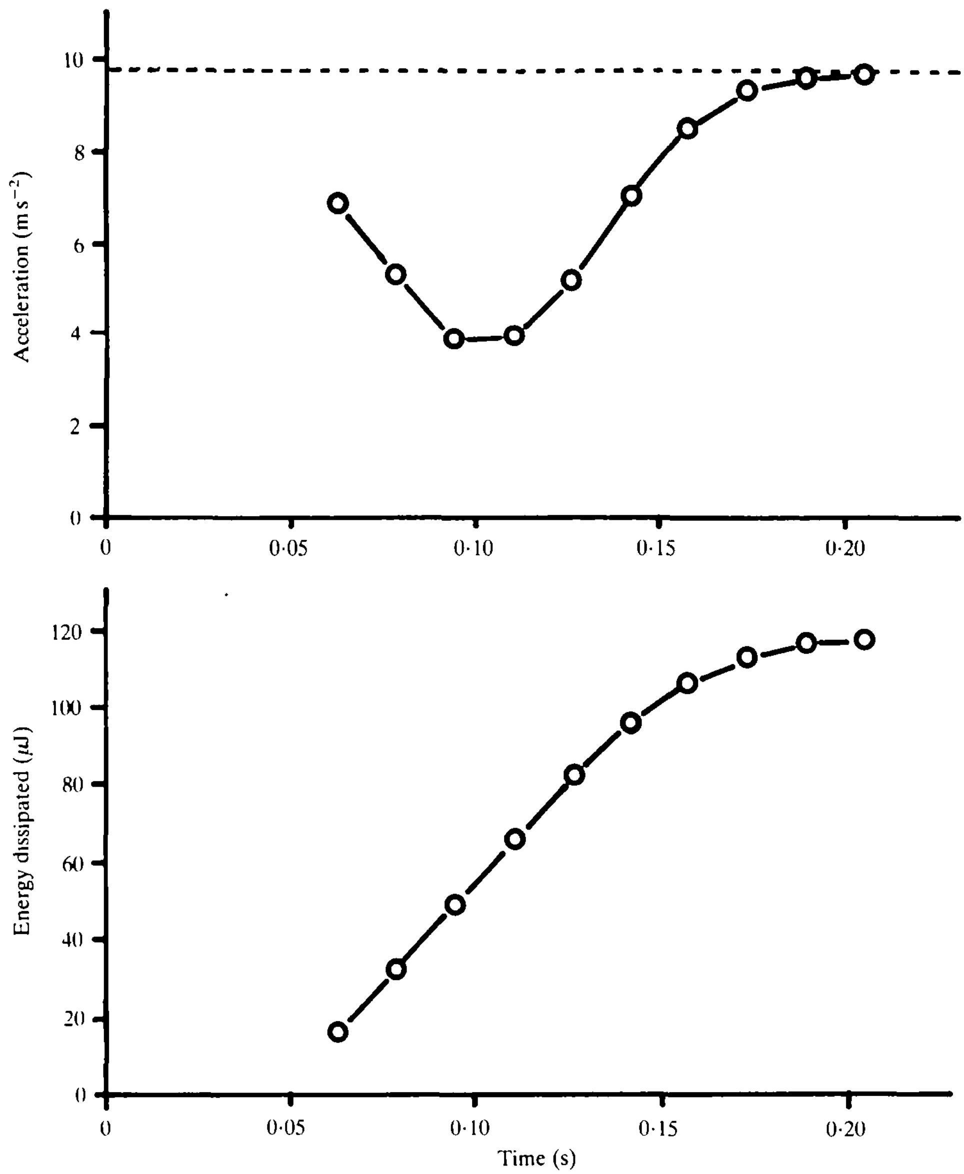

Fig. 4. Typical smoothed curves obtained from analysis of films of falling lead shot attached to drag-lines showing the acceleration of the falling shot and the amount of strain energy stored in the drag-line. The energy curve was calculated using equation (2).

energy used to fracture the silk ($AC \cdot l_o$) was taken to be equal to the calculated E_s at the time at which calculated acceleration first reached $\boldsymbol{g}$ (Fig. 4). This value was then divided by l_o to obtain AC.

The silk of the drag-line was very thin and could not be seen in the ciné films. Therefore, the failure of the drag-line could not be observed directly. Also, due to the effects of data smoothing, time of failure (t_f) could not be determined directly from sudden changes in gradient of velocity or acceleration curves. However, it has been shown (Fig. 3) that t_f can be determined indirectly from the location of a point of inflection P in the velocity-time curve and also from the time at which the corresponding acceleration curve reaches $\boldsymbol{g}$. The time of failure was thus estimated from both five-point velocity curves and nine-point acceleration curves and the mean value was calculated in each case. The length of the drag-line at failure, l_f was then obtained from the distance-time curve and breaking strain calculated from the equation:

$$\epsilon_f = (l_f - l_o)/l_o. \quad (4)$$

From the films of anaesthetized spiders falling without drag-lines, velocities were calculated using five-point smoothing. As there was no drag-line present, the total energy lost due to air drag, E_a, at any time was simply the difference between the potential energy lost by the falling spider and the kinetic energy it had gained. This was calculated using equation (2). In this case the energy dissipated, E_d, is equal to E_a.

From the films of spiders in controlled descent on drag-lines, velocities of descent and kinetic energies were calculated using five-point smoothing and accelerations using nine-point smoothing.

Table 1. *Values obtained for strain energy capacity per unit length and breaking strain of drag-lines produced by spiders of different masses*

Mass of spider, M (mg)	Strain energy capacity per unit length, AC (μJ m^{-1})	Breaking strain, ϵ_f
26	88	0·15
26	376	0·28
36	179	0·23
45	396	0·24
45	366	0·29
45	293	0·22
45	353	0·15
56	177	0·19
56	54	0·06
56	113	0·10
64	131	0·19
Means:	230	0·19

RESULTS

The values of AC and ϵ_f are not significantly correlated with the mass of the spiders ($P > 0.1$) (Table 1). This is consistent with the findings of Denny (1976) who was not able to demonstrate a significant correlation between spider mass and AC or ϵ_f of frame silk (which is produced from the same spinnerets as drag-line silk). Therefore, mean values of AC and ϵ_f were calculated and are shown in Table 1.

For a fall of 0·3 m, the mean value E_a for total energy lost due to air drag on a spider was 9·9 % of total potential energy lost (95 % confidence interval ± 1·1 %).

Films of spiders on drag-lines showed their controlled descents were very slow. Typical velocities were about $0.12\,\mathrm{m\,s^{-1}}$ and never exceeded $0.24\,\mathrm{m\,s^{-1}}$. Accelerations never exceeded $2.0\,\mathrm{m\,s^{-2}}$. Thus for a spider of mass 50 mg, typical maximum combined weight and inertia forces on its drag-line would be about 0·6 mN. The kinetic energy of spiders on the drag-lines was typically 0·33 μJ and never exceeded 2·6 μJ.

The mean diameter of individual strands of silk used in drag-lines was found to be 1·86 μm (95 % confidence interval ± 0·25 μm), giving mean total cross sectional area, A for the drag-line, which is composed of two silk strands, of $5.67 \times 10^{-12}\,\mathrm{m^2}$.

DISCUSSION

Two of the most important parameters affecting the factor of safety are the variability of loading and the costs of failure (Alexander, 1981). It is not the mean level of loading, but the higher loads which determine the 'safe' strength of a structure. Therefore, if two structures are subject to the same mean load but the loading on the first is more variable so that it is subjected to higher *maximum* loads than the second, then the first structure will have to be stronger to be as safe as the second. It would be expected for more variable loading to lead to increased safety factors.

If the drag-line supporting the spider should break and the spider falls to the ground what will be the costs of this failure? It is unlikely that such a fall will injure the spider and it may be that the only costs involved are the energy required for the spider to climb back up to its original position plus the loss of the drag-line. (It is known that spiders eat used silk, Peakall, 1971.) It may be that the spider cannot find its way back up to its web in which case there would be an additional cost due to the loss of the web and any food it contains or is likely to catch while the spider is constructing a new web, plus the cost of producing the new web. However, spiders may construct new webs at frequent intervals (Breed, Levine, Peakall & Witt, 1964) so even if the web is lost, costs of failure are likely to be low. Safety factor theory, not surprisingly, predicts that increased costs of failure lead to increased factors of safety in order to reduce the probability of expensive failures. Since costs of failure of drag-lines are likely to be low, it would be expected that their factors of safety would be low. Similarly it has been shown that the loading on drag-lines is of very low variability, depending only on the spider's weight and on variability in A. This would also promote low factors of safety.

Substitution of the mean values of AC and ϵ_f from Table 1 into equation (1) gives the result:

$$nW = 1{\cdot}1\times10^{-4}\,\text{N}. \quad (5)$$

This implies that a spider must have a mass of less than 11 mg in order to achieve a safety factor greater than 1 and, therefore, be 'safe' when using its drag-line! The spiders were bigger than this. It is clear that drag-lines are not capable of absorbing the full potential energy of falling spiders as strain energy and it has also been shown that energy losses due to air drag are small, but observations of active spiders in the laboratory or in the field show that drag-lines rarely fail during use. The solution to this apparent dilemma may be revealed if one considers a spider making controlled descents on its drag-line. In order to move downwards, the spider allows its weight to draw more silk from its spinnerets. As the strain energy in the silk will remain unchanged provided the spider descends at constant velocity during this procedure and energy losses due to air drag are likely to be negligible at the low velocities of controlled descent, then the energy required to draw silk from the spinnerets is equal to the difference between the potential energy lost and kinetic energy gained by the spider. Thus if the spider is *accelerating* downwards, the energy required to draw silk must be less than the potential energy lost and if it is *decelerating*, the energy required to draw silk must be greater than the potential energy lost. Thus it is clear that spiders are able to dissipate potential energy by drawing silk from their spinnerets and they can control the amount of energy so dissipated. A mechanism for this has been suggested by Work (1978). Observations of spiders in the laboratory showed that they were usually anchored to the substrate by a drag-line of about 5 cm in length. If they were dislodged they usually came to rest hanging on a line of between 10 and 20 cm in length. These spiders were obviously dissipating some of their potential energy by drawing silk. The implication of the result given in equation (5) above is that falling spiders must dissipate a considerable proportion of their lost potential energy in this way. For example, a spider of mass 45 mg would have a 'safety factor' of 0·27, thus it would have to dissipate, by drawing silk, a minimum of 73 % of the potential energy it lost in a fall from vertically above the point of anchorage of its drag-line.

Denny (1976), working on the frame silk of the argiopid spider *Araneus sericatus*, reported values for strain energy capacity of between 62 and 212 MJ m^{-3} and breaking strains of about 0·25. Corresponding values from the present study are mean strain energy capacity, $\overline{C}$, of 42 MJ m^{-3} and mean breaking strain, ϵ_f, of 0·19. The higher values reported by Denny may have been due to a number of reasons. His spiders were of a different species and were heavier, ranging in mass between 0·1 and 0·15 g compared to 0·026–0·064 g in the present study. This may have been reflected in the production of more robust drag-lines. However, Denny reported an average silk strand diameter of 1·9 μm, the same as in this study. Denny tested silks at very low strain rates of between 0·03 and 1·25 min^{-1} whereas the experiments described in this paper involved strain rates of about 50 min^{-1}. In this sense the present study tested the silk under more natural conditions. Nevertheless, if we consider a spider of mass

0·1 g, which was the lightest used by Denny, having fallen from directly above the point of anchorage of its drag-line, then using Denny's median values for strain energy capacity (137 MJ m^{-3}) and breaking strain (0·25) and assuming the drag-line to be constructed of two silk strands each of diameter 1·9 μm, the factor of safety for this spider would be 0·29. Thus Denny's results support the main conclusion of this study, that spider drag-lines are not able to absorb the full quantity of potential energy lost by a falling spider and the remainder must be dissipated by drawing more silk.

It has been argued that drag-line silk should have a low safety factor. However, the figures presented here are much less than 1 and are not true safety factors. They actually represent the maximum proportion of the potential energy lost by a falling spider which may be absorbed as strain energy in the drag-line. The spider is able to control how much energy is converted into strain energy in the drag-line and how much is dissipated by drawing silk (Work, 1978). This control, combined with a favourable loading regime and low costs of failure, allows spiders to use a very weak structure as a reliable safety line.

The work described in this paper was supported by a Science and Engineering Research Council research studentship. I am grateful to Professor R. McN. Alexander who made helpful comments on earlier drafts of this paper.

REFERENCES

ALEXANDER, R. McN. (1981). Factors of safety in the structure of animals. *Sci. Prog. Oxf.* **67**, 109–130.

ALEXANDER, R. McN. (1983). *Animal Mechanics*. 2nd Edn. Oxford: Blackwell Scientific Publications.

BREED, A. L., LEVINE, V. D., PEAKALL, D. B. & WITT, P. N. (1964). The fate of the intact orb-web of the spider *Araneus diadematus* Cl. *Behaviour* **23**, 43–60.

DENNY, M. (1976). The physical properties of spider's silk and their role in the design of orb-webs. *J. exp. Biol.* **65**, 483–506.

LANCZOS, C. (1964). *Applied Analysis*. London: Pitman & Sons, pp. 305–331.

LUCAS, F. (1964). Spiders and their silks. *Discovery, Lond.* **24**, 20–26.

PEAKALL, D. B. (1971). Conservation of web proteins in the spider *Araneus diadematus*. *J. exp. Zool.* **176**, 257–264.

PRANDTL, L. & TIETJENS, O. G. (1957). *Applied Hydro- and Aerodynamics*, 2nd. Edn. New York: Dover Publications.

WORK, R. W. (1978). Mechanisms for the deceleration and support of spiders on draglines. *Trans. Am. microsc. Soc.* **97**, 180–191.