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Tensile Characteristics of Squid Mantle

JIN-DER KUO, MICHA PELEG, and HERBERT O. HULTIN

ABSTRACT

The mechanical properties of cooked and uncooked mantles of *Loligo pealei* and *Illex illecebrosus* in uniaxial tension were characterized by strength, strain at failure, overall stiffness and curvature of corrected stress vs strain relationships which is associated with degree of strain hardening. All four parameters differed at different orientations to the squid's principal axis. Uncooked mantle was considerably stronger and stiffer in the longitudinal direction, showed a higher degree of strain hardening, but sustained a smaller prefailure strain. Cooking at 60°C and 100°C had a much more drastic effect on the mechanical behavior of longitudinal specimens than on the transverse. These anisotropic mechanical features are attributed to the orientation of the collagen fibers of squid.

INTRODUCTION

THE MECHANICAL PROPERTIES of squid mantle have been studied mainly through cutting and shearing devices (Otwell and Hamann, 1979b; Stanley and Hultin, 1982; Stanley and Smith, 1984; Kolodziejska et al., 1987) and to a lesser extent by compression (Shadwick and Gosline, 1984). Isometric tension was employed by Otwell and Hamann (1979b) to monitor the effect of heating. In such experiments, the overall sample dimensions remain practically unchanged during the test and only the force varies with time.

One of the features of squid mantle is that specimens cut from it can be gripped and subjected to an ordinary tensile test. The use of such a test eliminates the arbitrary elements and artifacts introduced by shear devices (e.g., the blade's thickness, distance, shape, etc.). Unlike compression, it is possible to test long specimens in tension and to control their orientation with respect to the squid axes at the same time. In principle, therefore, the tensile test is potentially a sensitive tool to assess mechanical properties of squid mantle in universal engineering terms that can be related directly to structural features.

In the outer tunic of the squid mantle, there are collagen fibers which have a specific orientation with respect to the mantle's major axis, i.e., 27° in *Loligo pealei* and 23° in *Illex illecebrosus*. The detailed three dimensional structure of the fibers and their orientation with respect to other axes was studied by Otwell and Hamann (1979a). Its biological function in locomotion is discussed by Ward and Wainwright (1972) and Shadwick and Gosline (1984). The role of the arrangement of the collagen fibers in textural evaluations is discussed by Otwell and Hamann (1979a; 1979b), Stanley and Hultin (1982) and Stanley and Smith (1984).

The existence of an oriented structure suggests that the mechanical properties of the squid mantle should be different in the longitudinal and transverse directions because at a given strain, or per cent deformation, there is a difference between the forces that stretch the collagen fibers and the forces that act to separate them. Since fibrous materials have maximum stiffness and strength in the general direction of the fibers (e.g., ropes), squid mantle is expected to be stiffer and stronger in the longitudinal direction. Furthermore, under large deformations muscle tissues are known to exhibit a behavior akin to strain hardening in engineering materials. The manifestation of strain hardening is that the stress is not proportional to the strain as in ideal elastic bodies but progressively increases with the strain almost until rupture (Yamada, 1970).

Strain hardening has not been thoroughly investigated in marine species. It has been speculated that stress hardening is due to the unfolding of coils and the creation of additional bonds between stretched fibers that come physically closer as a result of the reduction of the cross-sectional area of the specimen (Segars et al., 1981). If a similar mechanism occurs in squid mantle, then the degree of such "strain hardening" should also be higher in the longitudinal than in the transverse direction because of the characteristic collagen fiber orientation of the mantle (Fig. 1). Obviously, the mechanical properties of the mantle in the radial direction (perpendicular to the plane of the mantle) are different from those measured in the longitudinal or transverse directions. Due to the mantle thickness, however, it is difficult for technical reasons to prepare such specimens for a tensile test.

The objectives of this work were to test the applicability of a tensile method to squid mantle and to relate its mechanical behavior to the structural features of the mantle.

MATERIALS & METHODS

Materials

Squid of the *Illex illecebrosus* and *Loligo pealei* species having a mantle length of 11–18 cm were obtained from day boats in Gloucester, MA. They were cleaned (skin, tentacles and viscera removed)

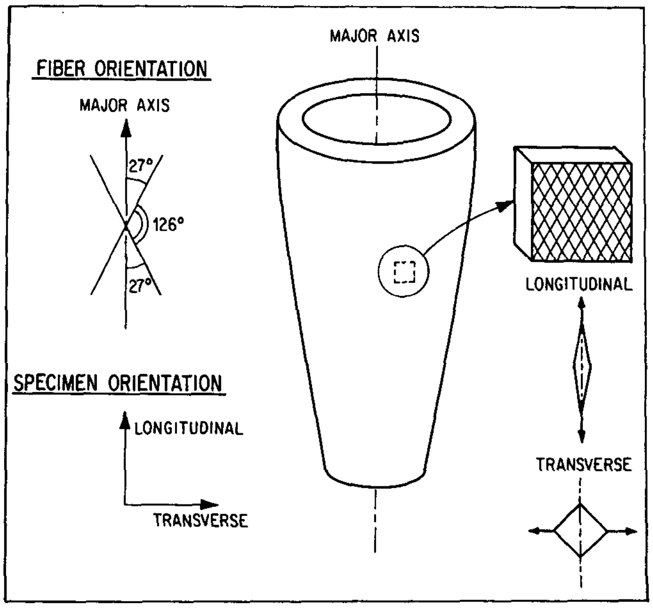

Fig. 1.—Schematic view of the geometry of squid mantle. Orientation of the collagen fibers with respect to other axes is not shown.

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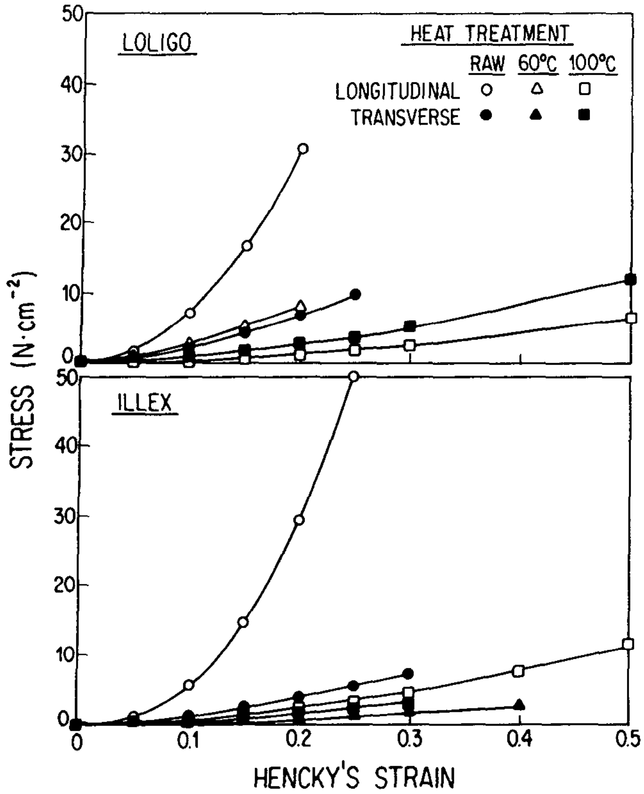

Fig. 2.—Typical corrected tensile stress vs. Hencky's strain relationships of specimens cut from the mantles of two squid species. [For the stress and strain calculation see Eq. (1) and (2).]

and cut open along the dorsal surface to yield flat mantles. These were packed in sealed plastic bags and stored at −40°C.

Sample preparation

Thawed mantles were either tested at room temperature (about 25°C) or cooked prior to testing. Cooking was done by heating the mantles in distilled water (1:60 squid to water, w/w) at 60°C or 100°C for 2 min followed by cooling to room temperature by rinsing with running tap water. Samples of squid mantle were cut in the shape of a dumbbell of overall length 4.5 cm. The widest portions at the two ends were 0.5 cm while the center of the dumbbell was 0.2 cm. The pieces of squid were cut from the mantles with an orientation either parallel to the longitudinal axis (longitudinal) or perpendicular (transverse) to it. The thickness of each specimen was measured with calipers. It was generally in the order of 0.4 cm with a scatter of about 10%.

Testing

The ends of the specimens were mounted on an Instron Universal Testing Machine, Model 1000 set in a tension mode. The upper grip was an "alligator" clip and the lower a standard tensile grip into which emery paper was inserted to increase friction. All specimens were deformed at a constant deformation rate of 2 cm·min^{-1}.

RESULTS & DISCUSSION

THE FORCE DEFORMATION curves of the squid specimens were transformed into corrected ("true") stress (σ_c) vs Hencky's ("true") strain (ϵ_H) by the following transformation (Richards, 1961):

$$\sigma_c = \frac{F(L_o + \Delta L)}{A_o L_o} \quad (1)$$

where F is the force, A_0 and L_0 the initial cross-sectional area and length of the specimen, respectively, and ΔL the absolute deformation,

and
$$\epsilon_H = \ln \frac{(L_o + \Delta L)}{L_o} \quad (2)$$

Typical stress-strain relationships of uncooked and cooked mantles of the two squid species are shown in Fig. 2. The failure conditions are summarized in Table 1. The scatter in the failure parameters expressed in terms of the coefficient of variation was on the order of 5–30% for the strain and 20–40% for the stress. Possible causes are slight thickness variation, some curvature and imperfect specimen shape. Also not excluded is a true variability in the mechanical properties of the mantle itself as a result of natural causes or accidental damage during preparation. Slip or premature failure at the grips, however, was not a cause and all the specimens failed in the center. The scatter that is reported in Table 1, therefore, should be considered as an upper limit of the natural nonuniformity of the mantles.

Despite the scatter, it was unmistakably clear that uncooked squid mantle had distinctly different mechanical properties in the longitudinal and transverse directions. This was evident in both the strength and the degree of stretch the specimens could sustain before failure in both species.

Both heat treatments (60°C and 100°C) caused strength reduction and considerable extension of the prefailure strain in the longitudinal direction. Cooking to 60°C caused more strength reduction in the longitudinal direction than cooking to 100°C. Since squid collagen begins to melt at about 60°C (Otwell and Hamann, 1979a), the differences in the mechanical behavior may be associated with the state of the collagen. In the transverse direction, heating to 100°C increased the prefailure strain. Prefailure strain was also increased in the transverse direction at 60°C in Loligo but not in Illex.

Shape characteristics of the stress-strain curves

The shape of all the stress-strain curves (Fig. 2) was concave upward which is a clear indication of "strain hardening." The simplest mathematical model that can describe such curves is:

$$\sigma_c = K\epsilon_H^n \quad (3)$$

Table 1—Tensile failure parameters of squid mantle[a]

			Longitudinal direction				Transverse direction			
			σ_f		ϵ_f		σ_f		ϵ_f	
Species	Heat treatment	No. of specimens	Mean (N.cm^{-2})	Cov (%)	Mean (−)	Cov (%)	Mean (N.cm^{-2})	Cov (%)	Mean (−)	Cov (%)
Loligo	uncooked	7	34	26	0.17	18	14	36	0.25	24
	60°C	7	5	32	0.22	27	12	26	0.35	9
	100°C	5	10	34	0.44	20	18	34	0.49	20
Illex	uncooked	6	58	20	0.29	14	13	28	0.41	17
	60°C	3	8	39	0.40	10	13	20	0.38	24
	100°C	4	23	36	0.60	8	10	38	0.55	5

[a] σ_f is the ultimate tensile strength and ϵ_f Hencky's strain at failure. For the specimen's orientation see Fig. 1.

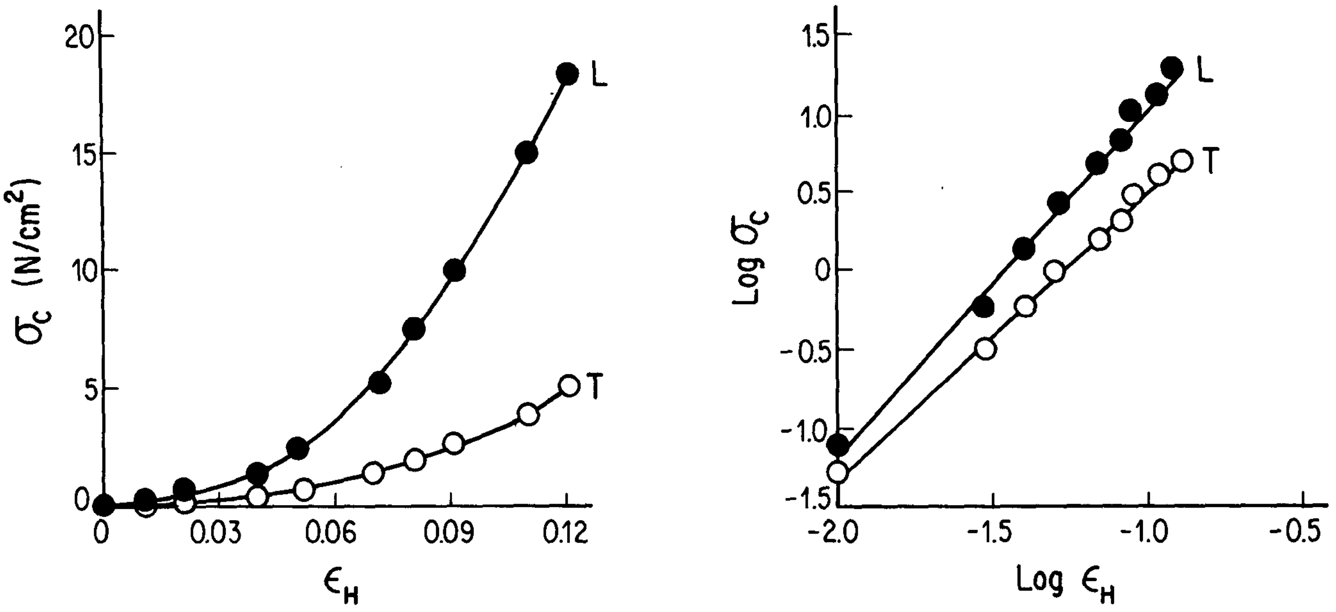

Fig. 3.—Raw and transformed tensile stress-strain relationships on squid mantle. σ_c - corrected stress, ϵ_H - Hencky's strain, L and T - longitudinal and transverse directions, respectively.

Table 2—Regression parameters of the tensile stress-strain relationships of squid mantle[a]

			Longitudinal direction					Transverse direction				
			K		n		r^2	K		n		r^2
Species	Heat treatment	No. of specimens	Mean (N.cm^{-2})	Cov (%)	Mean (–)	Cov (%)	Mean (–)	Mean (N.cm^{-2})	Cov (%)	Mean (–)	Cov (%)	Mean (–)
Loligo	uncooked	7	930	55	2.1	10	0.96	80	73	1.5	19	0.98
	60°C	7	110	150	1.6	17	0.95	30	60	1.4	17	0.96
	100°C	5	20	30	1.8	19	0.95	40	20	1.7	21	0.99
Illex	uncooked	6	1400	78	2.4	11	0.96	45	98	1.5	20	0.95
	60°C	3	33	33	1.9	7	0.95	10	46	1.5	1	0.98
	100°C	4	40	43	1.8	13	0.96	21	47	1.6	6	0.97

[a] For specimen orientation, see Fig. 1. The constraints were calculated from linear regression of Eq. 4. The fit of experimental data is also demonstrated in Fig. 4. K is a measure of stiffness and n of the degree of strain stiffening or hardening.

where the constant K being a scale factor is a measure of the sample's overall stiffness and n the extent to which the curve deviates from a straight line. Since this deviation is a manifestation of the extent of hardening or stiffening, the constant n can serve as a convenient hardening index. The values of K and n were calculated by linear regression of the logarithmic transform of Eq. (3), i.e.,

$$\log \sigma_c = \log K + n \log\epsilon_H \qquad (4)$$

The fit of Eq. 4 to experimental data of squid mantle, in the longitudinal and transverse directions, is demonstrated in Fig. 3. The mean values of K and n and their scatter in terms of the coefficient of variation are presented in Table 2. As could be expected in uncooked squid, n was much higher in the longitudinal direction than in the transverse. After cooking the values dropped but they were still consistently higher than those measured in the transverse direction. In the uncooked specimens, the difference between the longitudinal and transverse directions was even more noticeable in the magnitude of K. The value of K was calculated as an "intercept" (i.e., its value is the extrapolated stress at a unit strain, or $\epsilon_H = 1$ which is outside the experimental range). Therefore, its magnitude, unlike that of n which was calculated as a slope, was highly sensitive to minor deviations. This is one of the major reasons for the large scatter in its values, much higher than those of the other parameters, that is, n and strength and strain at failure. Despite the scatter, however, the value of K appears to be a reasonable measure of stiffness and a quantifier of orientational and heat effects. Although the values of K in general follow those of strength, the two are independent mechanical characteristics.

CONCLUSIONS

THE TENSILE PROPERTIES of squid mantle specimens can be determined by routine tests using a Universal Testing Machine with standard and/or simple devices to assure grip. The tensile properties of the mantle can be characterized by four independent parameters, namely strength (stress at failure), strain at failure, overall stiffness, and degree of strain stiffening or hardening. The magnitude of all four depends on the specimen orientation with respect to the squid's principal axis which is the result of the directional structure of the muscle and collagen fibers. Heat treatment affects the magnitude of all these parameters but not to the same extent.

The method appears to be reproducible and sensitive enough to detect and quantify textural changes in squid mantle. It also enables the expression of these changes in terms of universal mechanical parameters whose magnitude is least affected by instrumental artifacts.

REFERENCES

Kolodziejska, I., Sikorski, Z.E. and Sadowska, M. 1987. Texture of cooked mantle of squid *Illex argentinus* as influenced by specimen characteristics and treatments. J. Food Sci. 52: 932.
Otwell, W.S. and Hamann, D.D. 1979a. Textural characterization of squid

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