Available online at www.sciencedirect.com

ScienceDirect

Journal of Bionic Engineering 12 (2015) 453–463

Energy Absorption of Spider Orb Webs During Prey Capture: A Mechanical Analysis

Hui Yu, Jialing Yang, Yuxin Sun

Institute of Solid Mechanics, *Beihang University*, *Beijing* 100191, *China*

Abstract

When the spider orb web stops a prey, the web dissipates impact energy by three routes: internal dissipation within the radial silk, internal dissipation within the spiral silk and aerodynamic dissipation. This paper investigates the energy dissipation mechanism of spider orb webs from the mechanics point of view. Firstly, the dynamic response and energy dissipation of a single spider silk under transverse impact are studied analytically and numerically. The congruence of dynamic response curve validates the accuracy of finite element analysis. Then the whole web is modeled using the finite element method and the respective contribution of each route to total energy dissipation during the simulated prey impact is obtained, which agrees with published experimental results. Finally, the influence of initial impact kinetic energy on the fraction distribution of three routes is demonstrated based on the finite element model. The mechanical mechanism of energy dissipation of spider orb webs is discussed and the reason for the differences among the existing opinions is speculated.

Keywords: silk, spider webs, energy dissipation, finite element

doi: 10.1016/S1672-6529(14)60136-0

1 Introduction

As is known, spiders are the preeminent silk craftsmen, utilizing various types of silk threads to construct diverse webs to realize corresponding functions. Among these, more than 3000 species of spiders rely on orb webs to capture flying insect prey, which are ubiquitous predators in many terrestrial ecosystems[1]. The success of orb-weaving spiders makes them the dominant consumers at intermediate trophic levels[2].

The prey capture function of an orb web is attributed largely to the extraordinary properties of the silks used to construct the web[3–5]. For example, the spider *Araneus diadematus* constructs two-dimensional, round webs mainly by two types of silk: (1) the dragline silk composing the supporting radial threads and frame of orb web, which is produced by the Major Ampullate (MA) gland; and (2) the viscid silk spinning the capture spirals, which is produced by the Flagelliform (FL) gland. The MA silk has high stiffness and tensile strength while the viscid silk has low strength but high extensibility[6]. The MA silk is well known for its combination of strength and toughness, which is unrivalled in natural polymeric biomaterials and man-made materials such as Kevlar, carbon fiber and high-tensile steel[6]. As for viscid silk, its initial stiffness and maximal strain are comparable with those of synthetic rubber, but its strength is 10 times higher[6]. The combination of high strength and extensibility gives viscid silk toughness virtually identical to that of MA silk. The exceptional toughness of these two types of silk means their greater ability of absorbing energy before breaking.

Many works have highlighted spider silk itself, in aspects of evolution and ecology[7–9], biomaterial and biomechanical properties[10–12], nanostructure and molecular mechanics[13–15], biomimetics[16,17] and so on. However, it is the interplay between the web architecture and the biomechanical properties of silks that leads to the accomplishment of prey capture[18]. The orb web as a fine energy-absorbing structure characterized by its simplicity, compliance and light weight, has not been well recognized, which has the potential in developing the arresting net of carrier-based aircraft or the intercept net of high-altitude falling.

Corresponding author: Yuxin Sun
E-mail: yxsun@buaa.edu.cn

In nature, the prey is stopped successfully only when the web dissipates its kinetic energy without breaking. During prey-stopping, the kinetic energy of prey is transferred to the stretched silk. Unlike other biomaterials such as tendon that stores up to 93% of the energy input into their elastic deformation and then returns them[19,20], both MA silk and viscid silk dissipate more than 50% of the energy imparted to them by converting it to heat permanently as a result of the breaking of molecular bonds[21]. The spider silks must minimize internal storage of energy to prevent insects from 'catapulting' back out of the web after prey impact. On the other hand, the web oscillates during stopping insects. The relative motion between the threads and the surrounding air results in air resistance and the resistance force also contributes to the dissipation of the insect kinetic energy. Therefore, energy dissipation by orb webs can be partitioned into three components: (i) internal dissipation within the radial silk, (ii) internal dissipation within the spiral silk, and (iii) aerodynamic dissipation.

Now an intriguing problem comes: what is the respective contribution of these three routes during a prey capture? Which route is more important? At the earliest, Lin *et al*. conducted the finite element analysis and the pellet hitting experiments[22], and concluded that the aerodynamic damping accounted for a significant proportion of the energy dissipation by orb webs, but did not quantify the aerial damping energy directly. Alam *et al.* established another finite element model[23,24], also demonstrating the crucial role of aerodynamic damping. However, other studies ignored aerodynamic dissipation entirely when modeling the web[25,26]. Recently, Sensenig *et al*. directly measured energy dissipation by each of the three routes[27] and found that radial silk dominated energy dissipation and the capture spirals and aerodynamic drag contributed little for most orb webs, which is contradictory to the previous assertion. This confuses the issue and hence the objective function of aerodynamic dissipation in the function of orb webs is still unclear.

As the first step to develop the bionic cable net used in arresting and protecting system, understanding the energy absorption behavior of spider webs is crucial. Energy absorption was always analyzed theoretically in mechanics; however, the energy dissipation of spider orb webs has been rarely done like that up to now. Here, this problem is handled from the point of view of mechanics. We propose that the respective fraction of three routes in the total energy dissipation is related to the pre-impact kinetic energy of prey. To support this, first, a single silk thread under transverse impact is studied, in which the theoretical solution is given and the accuracy of finite element method is validated. Then, a finite element model of whole orb web is established to simulate realistic prey impact and the relative contributions of radial silk, the capture spiral and aerodynamic dissipation are investigated. The finite-element results agree with the previous experiments. Finally, the effect of initial kinetic energy of prey on web energy dissipation characteristic is disclosed and the previous different comments about the role of aerodynamic dissipation are explained.

2 Mechanical properties of silk

The soft silk can only be subjected to tension force and much research has been done on the silk properties[28–30]. Vollrath gave the stress-strain curves of MA silk under the cyclic tests[31], as shown in Fig. 1. The toughness and hysteresis of the silk are given by:

$$Toughness = A_1 + A_2,\quad Hystersesis = \frac{A_1}{A_1 + A_2}, \qquad (1)$$

where A_1 and A_2 represent the shadow area and grid area shown in Fig. 1 respectively.

When the MA silk is stretched, the stress-strain curve can be described by two stages, as shown in Fig. 1. At the initial segment ab, it is approximate straight line and the hysteresis is nearly zero. After the yield point b,

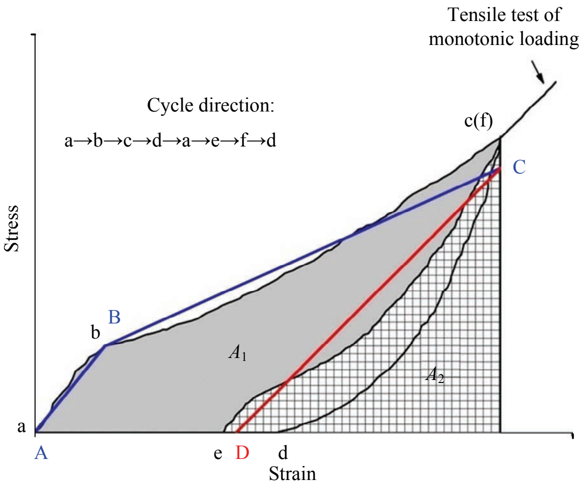

Fig. 1 Experimentally tested stress-strain curves of MA silk under monotonic loading and cyclic tests[31].