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Research paper

Exploring the shock response of spider webs

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ABSTRACT

Spider orb-webs are designed to allow for quick energy absorption as well as the constraint of drastic oscillations occurring upon prey impact. Studies on spider silk illustrate its impressive mechanical properties and its capacity to be used as technical fibers in composite materials. Models have previously been used to study the mechanical properties of different silk fibers, but not the behavior of the spider web as a whole. Full spider webs have been impacted by a projectile and the transverse displacement was measured by means of a laser interferometer. The damping and stiffness of the entire webs were quantified considering the orb-web as a single-degree-of-freedom (SDOF) system. The amplitude, the period duration, and the energy dissipation of the oscillations have also been reported from the experiments. The analysis of the energy dissipation confirmed that the webs of orb-web spiders are optimized for the capture of a single or few large prey, rather than several small prey. The experiments also confirmed that the overall stiffness of the web displayed a non-linear behavior. Such non-linearity was also observed in the damping characteristics of the webs studied.

1. Introduction

The mechanical performance of spiders webs allows them to absorb the energy of flying prey (Blackledge and Hayashi, 2006; Elices et al., 2009). Spider silks must have enough strength to absorb the kinetic energy of flying insect prey, while also minimizing the return of that energy to the prey in order to prevent it from bouncing off the web (Kelly et al., 2011). Spiders use different types of silks such as viscid, dragline, spiral, and cocoon silk (Gosline et al., 1986), each of which has different mechanical properties and functions. The primary silks composing the web are the dragline and viscid silks; the structural radial threads of the orb webs are made from dragline silk (Pérez-Rigueiro et al., 2010), whereas the spiral threads are made from viscid silk. The spiral threads are glue-coated and capture the prey (Torres et al., 2014), and it has been hypothesized that these spiral threads function as shock absorbers through viscous dissipation as kinetic energy is converted to heat (Denny, 1976).

Spider orb-webs are designed to allow for quick energy absorption as well as the constraint of drastic oscillations, which occurs upon prey impact (Du et al., 2011). These vibrations are used by spiders to locate and attack prey. Barrows (1915) reported that *Epeira sclopetaria*, an orb-weaving spider, orients itself in the center of the web in order to charge and seize flies that impact the web (Parry, 1965).

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Moreover, Craig et al. (1985) reported that small spiders build oscillating webs, and those webs characterized by large amplitude oscillations are able to intercept small, slow flying prey more efficiently than webs characterized by small amplitude oscillations.

Sensenig et al. (2012) reported that in a web of *Araneus trifolium* impacted by a projectile of approximately 180 μJ of kinetic energy, most of the energy transfer occurs in the first 100 ms, while the remainder occurs in subsequent oscillations. The study also found that the web could oscillate more than six times; however, only negligible energy remains after the first two oscillations. This is supported by a study by Alam et al. (2007), which also reports that the maximum dynamic response is found in the first natural frequency of the web.

Dynamic mechanical analysis (DMA) tests of individual spider threads have been reported in the literature (Blackledge et al., 2005; Torres et al., 2013). Blackledge et al. (2005) found that the loss tangent of spider silk rapidly increases during the first 2–3% of strain, and reaches a maximum at the yield point. They also reported an initial storage modulus of 9–11 GPa for the first 2% of strain for the fibers of different types of spider silk. At these small strains, low damping levels can be expressed. This, according to Kelly et al. (2011), allows orb webs to retain full functionality of their silk until the impact of a larger, more energetically valuable prey. By contrast, at relatively high strains under repetitive loading conditions, orb webs from species such as *Argiope aurantia* or *Argiope trifasciata* exhibit damping capacities of 40–50% (Kelly et al., 2011).

Studies on spider silk illustrate its impressive mechanical properties and its capacity to be used as technical fibers in composite materials. Bai et al. (2006) reported that silk can be modified for direct use in micro-electromechanical systems or as a part of a special composite material that enhances mechanical properties. Moreover, Allmeling et al. (2006) reported that spider silk is resistant to fungal and bacterial decomposition and that its molecular structures promote cellular adhesion and migration, making it an ideal biomaterial candidate.

Models have previously been used to study the mechanical properties of different silk fibers, but not the behavior of the spider web as a whole. Porter et al. (2005) developed one such model, taking into account the chemical composition and semi-crystalline morphology of the fibers. A molecular model of dragline silk elasticity has also been developed to reproduce the complex stress–strain curves for the dragline in wet and dry states (Termonia, 1994).

Additionally, studies have used projectiles simulating flying prey to study the energy absorbed and dissipated by spider webs (Kelly et al., 2011; Sensenig et al., 2012, 2013, 2010). Sensenig et al. (2012) used video-based imaging methods to measure the length change of the silk threads of orb webs during the projectile impact. By using the damping capacity measured for individual threads, the energy absorbed and dissipated by the entire orb web was estimated for different species of spiders.

In this study, we used an experimental setup that allowed us to directly measure the vibration of a spider orb-web as a whole. The aim of this work is to quantify the characteristics of the vibrations caused by prey impact in order to be able to establish the mechanical properties of orb-webs, under the assumption that such vibrations are forced vibrations of a damped, single degree of a freedom, spring mass system.

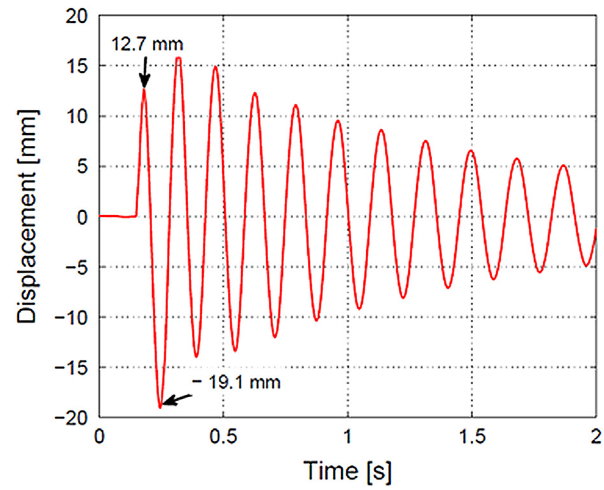

Fig. 1 – Variation of displacement with time during a projectile impact.

2. Results and discussion

For the experiments reported here a disk was attached to the center of the web and the position, and velocity of that disk was measured while being impacted by a projectile. Fig. 1 shows the horizontal displacement of the disk during the impact. A decaying amplitude of the oscillations can be observed as a function of time. The first deflection represents the displacement during the first impact of the prey. This effect allows the web to absorb high kinetic impacts that would otherwise cause an extension above the elastic range and therefore destroy the web. A similar response has been reported for a single spider silk thread by Du et al. (2011). These results are also in agreement with the results reported by Sensenig et al. (2012). In those experiments, the energy dissipation in orb webs spun by diverse species of spiders was estimated using data derived from high-speed videos of web deformation under prey impact together with the damping properties of individual threads. They estimated that most of the energy damping occurred within 0.1 s and that approximately 50% of the remaining prey energy was dissipated at each subsequent oscillation.

For our analysis, the dynamic behavior of the web system studied here was represented by a single-degree-of-freedom (SDOF) system. Linear SDOF systems are commonly used to describe the vibration of simple systems. In this type of systems, stiffness and damping are constants. A linear model, however, was not able to represent the behavior of the system during the first damped vibration in the experiments reported here. Non-linear SDOF systems have been used in cases with dry friction, Coulomb damping and non-linear stiffness (Chen and Tomlinson, 1996). We have also used a dynamic non-linear model to fit our experimental data considering that stiffness and damping were not constant. Fig. 2 shows the horizontal displacement of the disk