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DOI
10.12783/asc36/35746

Publication date
2021

Document Version
Accepted author manuscript

Published in
36th Technical Conference of the American Society for Composites 2021

Citation (APA)
Behling, E. R., Srivastava, A., Glaesener, R., Kumar, S., & Vashisth, A. (2021). What if spiders made metamaterial webs using materials with mechanical size-effects? In O. Ochoa (Ed.), *36th Technical Conference of the American Society for Composites 2021: Composites Ingenuity Taking on Challenges in Environment-Energy-Economy, ASC 2021* (Vol. 1, pp. 91-100). Destech publications. https://doi.org/10.12783/asc36/35746

COVER SHEET

Title: What if Spiders Made Metamaterial Webs using Materials with Mechanical Size-Effects?

Paper Number: 19

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ABSTRACT

Spider's webs are elegant examples of natural composites that can absorb out-of-plane impact energy to capture prey. Different spiders have different methods and structure of webs, and these variations in topologies have a significant effect on the prey catching abilities of the web. Taking inspiration from the spiders, metamaterials that have architectured topology can be fabricated according to end applications such as energy absorbers or impact tolerant materials. In this investigation, we theoretically examined impact loading on various orb-spider webs modeled with metamaterial architecture using materials that show size-dependent behavior. Using the size-dependent properties of nano-reinforced polymer-derived ceramics (PDCs), various metamaterial topologies were evaluated for out-of-plane impact due using ANSYS Ls-Dyna. The material properties capture the size dependency of the ceramics where smaller elements have higher strength due to reduced flaw intensity; the mechanical strength of these elements does not follow the conventional Griffith Theory. In this study, spider web geometries fabricated with PDCs with varying size elements were examined.

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INTRODUCTION

Over the course of evolutionary history, countless species of spiders have developed, optimized, and mastered the production of biologically produced web structures with the desire to ensnare and consume prey. This competitive biological advantage has led to hundreds of millions of years of iterative, evolutionary optimization of these structures [1], [2]. Among spiders, there is a wide variety of web architectures, including but not limited to sheetwebs, funnel-webs, orb-webs, and cob-webs [3]. These webs differ in architecture with varying degrees of asymmetry, material, or mode of prey capture but all share the fundamental objective to obtain food for the spider.

Web weaving spiders are biologically diverse and as such their silk can vary in different spider species. Web weaving spiders can differ in their material properties such as mode of silk synthesis, constituent proteins and amino acid structures; and their response to external environmental conditions such as wind, light, temperature or even gravity [4]. Despite differences that exist between individual spiders, orb weaving silk can be universally grouped as having remarkable mechanical capabilities. Spider silk has a composite microstructure with stiff anti-parallel beta sheets embedded in a matrix of amorphous amino acids [4], [5]. Spider frame silk exhibits high modulus of elasticity, strength, and energy absorbed at fracture with the advantage growing further when normalizing these properties with respect to weight [5]. Additionally, spider silk is highly hysteretic resulting in impact energy dissipating as heat, decreasing energy available to drive fracture [5]. These properties are conducive to the generation of an impact resistant system.

For the context of this research, our primary focus and source of inspiration are traditional orb webs (**Figure 1**), common to most outdoor spider species. Orb spider webs are typically characterized by a central hub consisting of both radial and spiral silk threads [6]. The design of orb webs involves the nuanced interplay between structural integrity and biological energy conservation. Radial threads are on average stronger than their spiral counterparts but require far more energy consumption to synthesize [7]. Balancing energy deficits motivates a spider to construct webs that simultaneously optimize structural integrity while minimizing energy consumption [1]. In the classification of orb webs, the degree of asymmetry, verticality, and mode of silk production are often distinguishing factors of the orb web. The decision process provides additional considerations for both recycling of web features as well as the construction of sacrificial elements [1], [8]. There is an extreme degree of variance among members of the orb weaving family and an enumeration of every exception or deviation would be outside the scope of this paper, however the extraordinary properties of the design warrants further examination.

The importance of impact strength is commonplace in nature and can be found in a diverse selection of biological systems. From nuts and fruits, elk antlers and ram horns, to woodpecker skulls, the importance of not only durable materials but their overlap with overall architecture cannot be understated. In nature, hierarchical structures that enhance the overall performance are not uncommon [9]. Such structures can include varying layers of material strength, different degrees of viscoelastic damping or gradients of both material performance or composition. These designs have found natural homes in a wide variety of engineering fields such as developing alternative steel alloys suitable for impacts in the automotive industry or body armor applications [10]. While metamaterials focus on using the topological architecture of the system to improve a property [11], by tailoring material properties in such structures could be more fruitful. This can be achieved by using materials with the same material chemistry but exhibiting varying properties as a function of the element size.

Man-made 1-D materials have been processed that show exceptional elastic modulus and strength [12], [13]. These include carbon nanotubes, nanofibers and ceramic fibers that can perform in harsh conditions such as high temperatures and corrosive environments [12]–[15]. These fibers can have modulus as high as 300 GPa and can reach strengths of ~8 GPa [16]; and subsequently, absorb a significant amount of energy. Interestingly, the strength of these fibers is dependent on the element size or the diameter of an individual fiber. Researchers have shown that these 1-D materials do not follow the Griffith theory where the strength of the material is inversely proportional to the square root of flaw that an element can house. This is because the density of the voids or flaws in the material reduces rapidly with decreasing diameters until it becomes flawless structure. [17]

In this investigation, we will examine orb-web spider webs made from ceramic nanofibers with varying size-dependent strength properties. The motivation for using such a spider web comes from the studies that suggest that spiders use multiple glands with different types of silks. The decision to use a particular type of silk is inspired by the fact that they have a limited amount of certain types of silk/protein and a goal to make a mechanical structure that can withstand out-of-plane impact in the form of the prey.

METHODS AND SIMULATIONS

Spider-web Virtual Fabrication

Taking inspiration from spider webs, we selected four different types of webs found in nature; these were Caerostris Darwini, Araneus Diadematus, Zilla Diodia, and Cyclosa Oculata as shown in **Figure 1** [18]–[20]. An in-house code was then used to build meta-material web structures inspired by the webs shown in **Figure 1**. These webs had a diameter of 200 mm. Spiders have multiple glands and the ability to secrete different types of silk; taking inspiration from this we used four different types of material properties for the meta-material web. The web consisted of three different types of geometries, namely triangles, hexagons, and auxetic hexagons as shown in **Figure 2**. Each of these geometries was concentrated in regions that had similar material properties. Four different material properties were used for regions with triangles, hexagons, auxetic hexagons, and attaching linear threads.

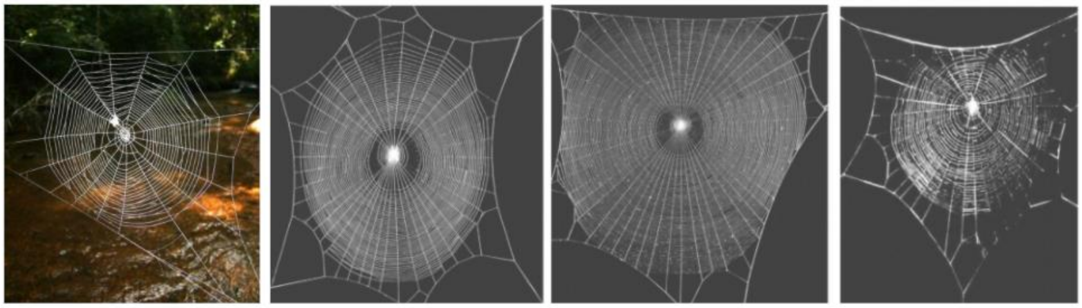

Figure 1. Orb webs made by Caerostris Darwini, Araneus Diadematus, Zilla Diodia, and Cyclosa Oculata spiders.[18]–[20] (*Images Reproduced by Permission of Dr. Samuel Zschokke*)

Next, each of these regions was assigned different material properties; the material properties for elements used for making the spider web were selected from Vashisth et al. [17]. The size-dependent nature of polymer-derived ceramics was used for the material properties of the 1-D elements. Three different element diameters were selected for each region; these three regions are shown in **Figure 3**.

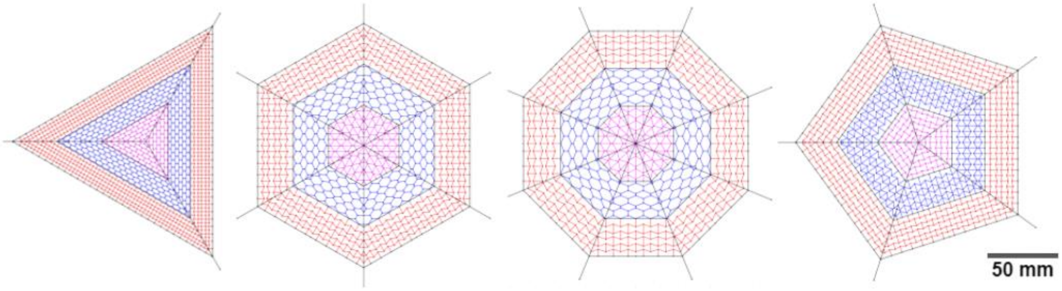

Figure 2. Nature-inspired spider metamaterial spider web structures for Caerostris Darwini, Araneus Diadematus, Zilla Diodia, and Cyclosa Oculata spider webs.

Since it is known that the radial threads are stronger than the spiral components [7], we assigned the highest strength properties to these threads (point A in **Figure 2**). These threads had a strength of 8.5 GPa, which is the strength of flawless polymer-derived SiOC ceramic fibers. The other three regions were assigned material properties such that the innermost region (shaded pink in **Figure 2**) had a higher strength followed by the intermediate region (shaded Blue in **Figure 2**) and the outermost region (shaded by red in **Figure 2**). The strength of the threads in the innermost, intermediate, and outermost region was assigned to be 3.3 GPa, 1.7 GPa, and 1.1 GPa respectively. In this manner, we ensured that four different material properties were used for the meta-material web, in a similar fashion as natural spider webs.

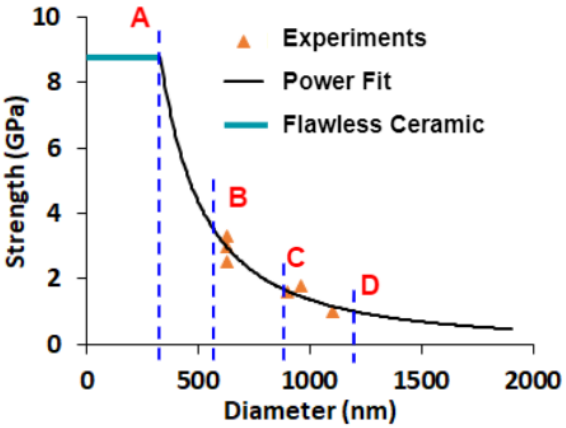

Figure 3. Size-dependent strength of SiOC polymer-derived ceramics that were for defending the material properties of meta-material spider webs.

Finite Element Simulations

The simulations were performed using ANSYS Ls-Dyna finite element simulation software that can perform non-linear dynamics simulations. The spider web was modeled as bar elements with linear elastic behavior until failure. The links between two elements were perfectly bonded to each other and the radial threads were fixed at the ends. The impactor was modeled as a solid element with a mass of 10.8 g and a diameter of 20 mm. An initial velocity of 100 m/s was provided to the impactor; the speed of the impactor was tracked along the z-direction (out-of-plane) from the web as well as the resultant velocity. The impactor was initially placed exactly above the center of the web and the gravitational forces are present along the negative z-direction.

RESULTS AND DISCUSSION

The impactor starts off with an initial velocity of 100 m/s and deaccelerates as soon as it comes in contact with the web. The resultant velocity profiles for each of these webs are shown in Figure 4, note that the impactor starts off with 100 m/s velocity, but due to the nature of the web architecture, the direction of the impactor changes during the impact in all the cases examined. Figure 4a shows the velocity component of the impactor only in the z-direction; note that the velocity of the impactor in the case of the Cyclosa Oculata web drops significantly as compared to the other web structures. This is mainly because the other web structures fail within the first 4 ms of the simulations. On the other hand, the resultant velocity of these specimens shows similar velocities for the Caerostris Darwini, Araneus Diadematus, and Cyclosa Oculata webs after 6 ms.

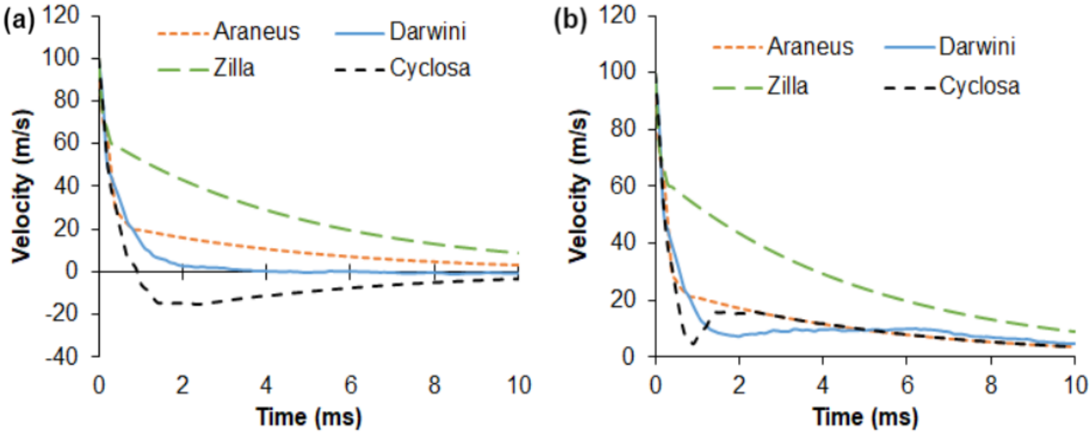

Figure 4. (a) Velocity of the impactor in the z-directions; (b) Resultant velocity of the impactor over the course of the simulation.

We also calculated the rate of change of velocity of the impactor before the failure of any element in the web. The average de-acceleration of the impactor was calculated for the first 0.3 ms of the impact by fitting a linear regression to the velocity-time profile in the z-direction (**Figure 5**). We see that the Cyclosa Oculata web resulted in maximum de-acceleration followed by Caerostris Darwini, Araneus Diadematus, and Zilla Diodia. It should be noted that the Cyclosa and Caerostris webs have a significant number of auxetic hexagons; these shapes have a negative Poisson ratio and are able to absorb more energy before failure as compared to triangles and hexagonal elements of the web.

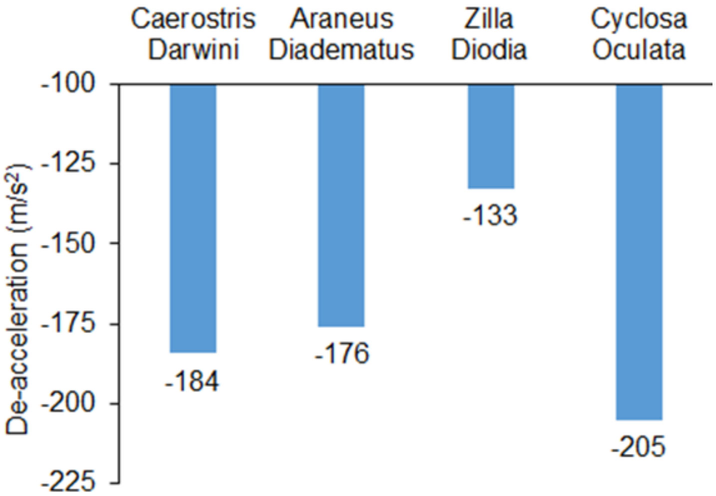

Figure 5. Deacceleration of the impactor in the z-direction.

Of all the webs that were examed, Caerostris Darwini had a triangular exterior structure. The web had hexagons and auxetic hexagons in the interior structure; the radial threads that held the whole structure together had the highest strength. The impactor experiences a de-acceleration of 184 m/s^2 over the first 0.3 ms; eventually coming to zero velocity component in the z-direction. One of the radial hubs fails at 3 ms (**Figure 6**) and no failure is experienced in the main web structure. On failure at one of the end hubs, the web warps around the impact and changes the direction of the impactor, resulting in velocity in the X-Y plane.

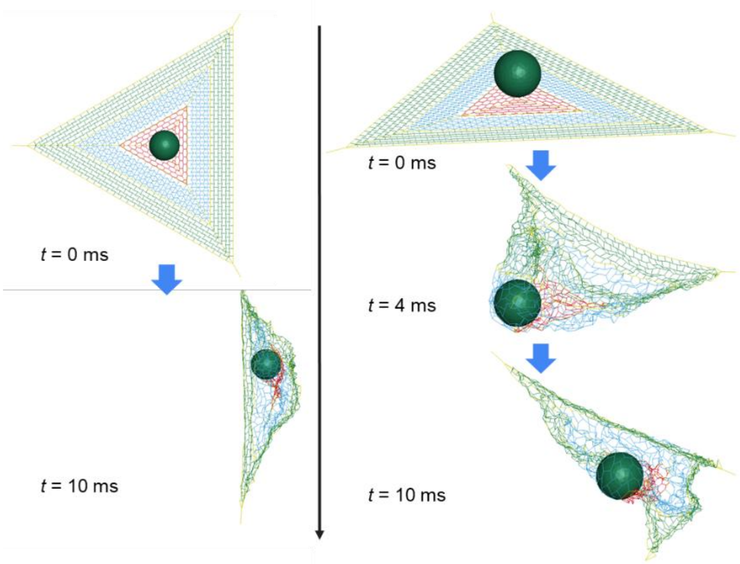

Figure 6. Snapshots of the simulations of impact on Caerostris Darwini web. Top view at times 0 and 10 ms are shown on the left and isometric view at times 0, 4, and 10 ms are shown on the right.

Araneus Diadematus was modeled as a six-sided web as shown in **Figure 7**. The web also failed within the first few ms of the simulation; the failure was due to failure at the nodes of the innermost section. Similar type of failure of the web was observed in Zilla Diodia webs as shown in **Figure 8**. It can be inferred from the velocity and the acceleration profile of these two webs that Araneus Diadematus was able to store more kinetic energy of the impactor as compared to Zilla Diodia.

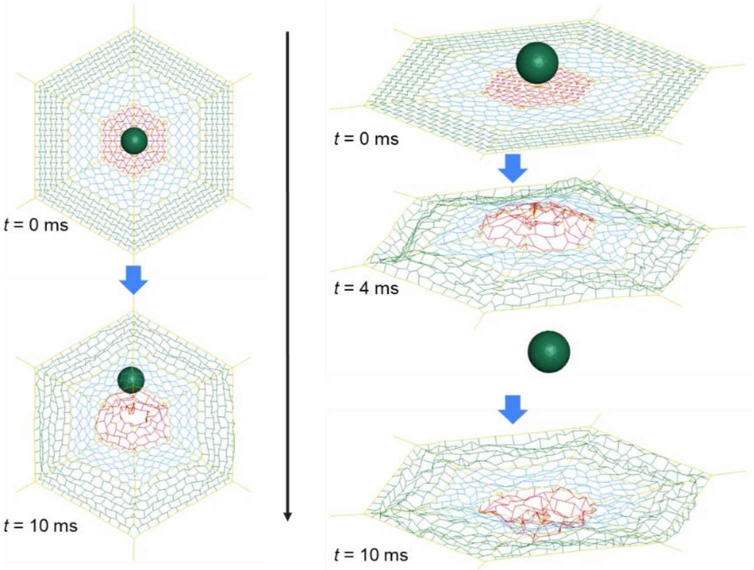

Figure 7. Snapshots of the simulations of impact on Araneus Diadematus web. Top view at times 0 and 10 ms are shown on the left and isometric view at times 0, 4, and 10 ms are shown on the right.

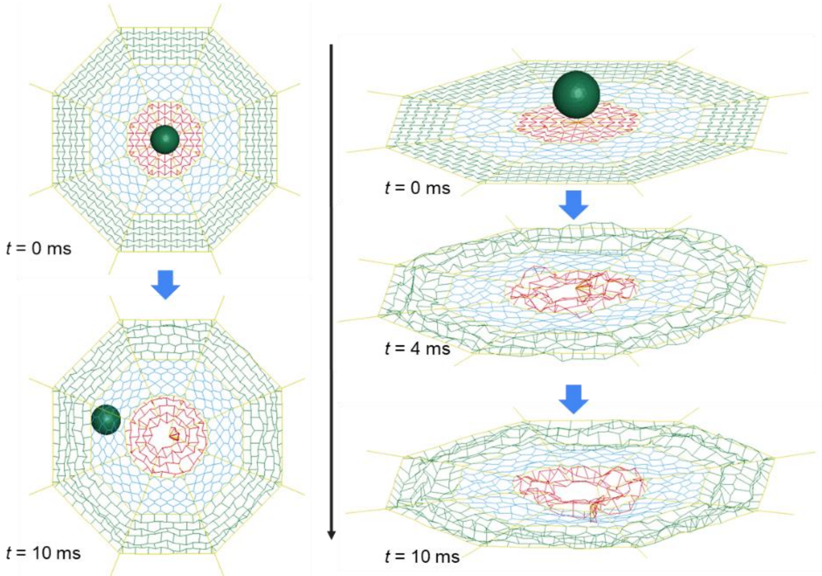

Figure 8. Snapshots of the simulations of impact on Zilla Diodia web. Top view at times 0 and 10 ms are shown on the left and isometric view at times 0, 4, and 10 ms are shown on the right.

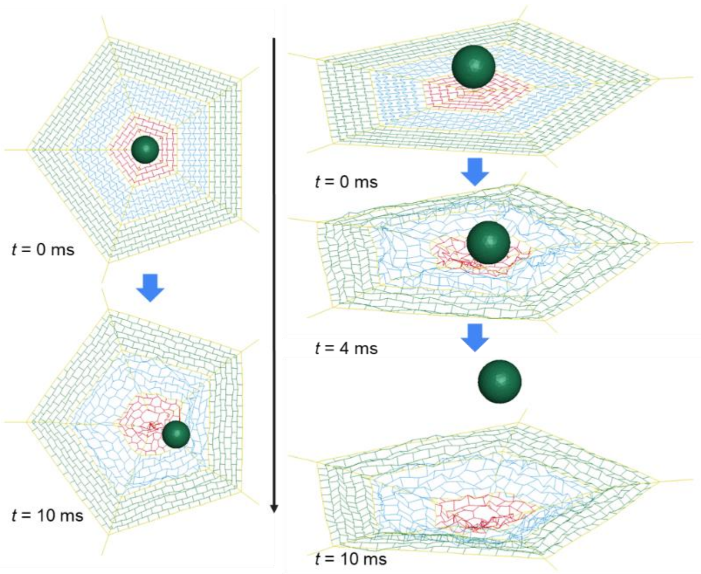

Figure 9. Snapshots of the simulations of impact on Cyclosa Oculata web. Top view at times 0 and 10 ms are shown on the left and isometric view at times 0, 4, and 10 ms are shown on the right.

Finally, we examined Cyclosa Oculata web, and as seen in **Figure 9**, this web did not fail due to the impact. This impact resistance can be attributed to the architectured structure of the web with significant coverage with auxetic hexagons. As shown in **Figure 4a**, the impactor bounces back after the impact with velocity reaching ~20 m/s just after the impact. Further, the transfer of kinetic energy to internal energy of the web, and in-turn conversion of kinetic energy of impactor can be seen in **Figure 4b**; this can be seen in the small dip in velocity-time profile.

While only four designs are considered here as the first work in this direction, the metamaterial web topology offers a large and seamless design space (and in turn, property space) in terms of tunable topology (e.g., the shape of the created by the connectivity of the webs) as well as material property (via spatially varying diameter of the polymer-derived ceramics). Due to the high dimensional design space, identifying the optimal design, e.g., for maximum impact absorption or deflecting the impactor with a target rebound velocity, may be challenging. Future work in this direction will include inverse design of such metamaterial webs with tailored mechanical response using data-efficient machine learning techniques [21].

CONCLUSION

In this investigation, we examined metamaterial spider webs inspired by natural spider structures. Inspiration was derived from Caerostris Darwini, Araneus Diadematus, Zilla Diodia, and Cyclosa Oculata spider webs, and metamaterial structures were designed. These metamaterial structures consisted of triangles, hexagons, and auxetic hexagons patterned on radial threads; similar to the circular patterns seen on natural spider webs. 1-D elements that make up the spider web were modeled as polymer-derived ceramic fibers that show size dependent behavior. To mimic the spider web constructure, four different material properties of these SiOC ceramics were chosen related to different element diameters. We found that webs with significant amount of auxetic hexagons showed better impact tolerance. Of all the webs tested, Cyclosa Oculata was the only web that survived the impact and showed highest deacceleration of the impactor.

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