Manufacturing Rev. 11, 12 (2024)
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https://doi.org/10.1051/mfreview/2024011

Manufacturing Review
Available online at:
https://mfr.edp-open.org

Research article   Open Access

Porous material energy absorbing structure based on spider web biomimetic structure

Deqiu Zhang and Jingyan Wang*

School of Civil Engineering, Harbin University, Harbin 150000, China

Received: 14 December 2023 / Accepted: 1 April 2024

Abstract. In the context of environmental protection and energy conservation, it is of great practical significance to study the design of porous material energy absorbing structures on the ground of spider web biomimetic structures. This study designs a porous material energy absorbing structure on the ground of a biomimetic spider web structure. Through in-depth research and experiments, the characteristics of this structure in efficient energy absorption are demonstrated. It has three types of energy absorbing structures: simple design, spiral and composite. The experimental data showed that the simple structure exhibited an energy absorption of 50 mJ under a 5J impact force, with an energy absorption efficiency of 10 mJ/g. At a 20J impact force, the energy absorption reached 200 mJ and the energy absorption efficiency was 40 mJ/g. Under parameter optimization, the cross-sectional diameter of the spiral and the cross-sectional area of the radial significantly affected the energy absorption effect. Reducing the cross-sectional diameter of the spiral from 0.55 mm to 0.45 mm would result in a decrease in energy absorption from 1.775J to 1.59J. When the cross-sectional area of the radial line changed from 0.5 to 0.45, the energy absorption effect decreased from 1.775J to 1.644J. Under static load, the composite structure had a 700 N triggering force and lower peak stress compared to the spiral structure under a compression displacement of 10 mm without compaction. The comprehensive performance of the composite structure is superior. This study provides a reference for designing more efficient and reliable energy absorbing materials, and the results have theoretical significance and practical application value. On the ground of experimental data and conclusions, biomimetic spider web structures can achieve safe, efficient, and reliable energy absorption protection in modern industrial applications, providing important theoretical support and technical guidance. The study of the energy absorption structure of porous materials based on spider web biosimulation has important theoretical and practical value in improving the safety, efficiency, and reliability of modern industrial applications. It provides a new direction and strategy for the development and application of high-performance energy absorption materials.

Keywords: Spider web structure / structural optimization / biomimetic materials / optimization strategy / porous medium

1 Introduction

As the boost of technology and the continuous improvement of industrial production, mechanical equipment requires higher safety and stability in complex environments such as high-speed operation and high load operations. Porous materials have gradually become an effective way to solve this problem due to their excellent characteristics such as lightweight and high strength. Among them, porous materials on the ground of Spider Web (SW) biomimetic structures have enormous research value and application potential in the field of energy absorbing structure design [1–3]. As a typical biological structure, SWs have high research value in the field of biology. The SW structure has good stability, strength, and superior energy absorption (EA) performance, which has attracted many researchers to imitate and simulate it. Due to its exceptional mechanical properties, the use of SW structures in the design of porous materials has garnered increasing attention. The structural design mimicking spiderwebs can significantly improve the toughness and EA efficiency of materials, especially in the development of lightweight high-strength materials. For instance, composite materials with high impact absorption capacity can be designed by simulating the radial and spiral structure of SWs. These results have a wide range of applications in fields such as automobile safety and building shock

* e-mail: wangjingyan202208@126.com

resistance. Furthermore, the SW-inspired design not only enhances mechanical properties but also improves the material's versatility, including self-healing ability and environmental adaptability. In recent years, research on SW structures has gradually expanded from the biological field to multiple fields such as materials science and engineering structures. The SW structure plays an increasingly important role in the design of porous materials. Combining the advantages of SW structure, the biomimetic design concept provides useful reference for porous material design. On the other hand, with the increasing demand for material performance, the application range of energy absorbing materials in multiple fields is also constantly expanding. Traditional energy absorbing materials have certain limitations, such as susceptibility to environmental changes and susceptibility to damage [4–6]. To address these issues, researchers are actively exploring new high-performance energy absorbing materials. The biomimetic porous materials on the ground of SW structure provide important research directions for the design and application of energy absorbing structures due to their unique structural advantages. At present, certain achievements have been made in biomimetic research on SW structures, such as mechanical performance models and biomimetic optimization design methods. However, in practical application fields, porous material energy absorbing structures on the ground of SW biomimetic structures are still in the exploratory stage, and there are still many shortcomings in their design methods, mechanical performance research, and application prospects. The complex environmental factors that energy absorbing materials face in practical application scenarios include impact loads, multi axial stress effects, etc. How to construct a more accurate SW structure EA model and how to better apply biomimetic SW structures to the design of porous materials has become an urgent problem that needs to be solved [7,8].

This study conducts in-depth research on porous material energy-absorbing structures using biomimetic theory and research results from SW structures due to the shortcomings of existing research in this area. Firstly, it analyzes the mechanical properties of the SW structure and its advantages and disadvantages in the design of energy absorbing materials. Secondly, it explores the application conditions of SW structures in porous materials and proposes a biomimetic design concept with universal applicability. Then, it conducts biomimetic design analysis for various working conditions in practical application scenarios to achieve the goal of optimizing EA performance. Finally, it improves the existing biomimetic energy absorbing structure on the ground of SW structure and proposes a new porous material design scheme. The aim is to provide theoretical support and practical guidance for further improving the performance of energy absorbing structures.

To meet the challenges of complex environments during high speed/load operations, mechanical equipment with higher stability and safety is required. Conversely, during low speed/load conditions, equipment performance requirements are relatively low, but there are still certain efficiency and reliability requirements for energy absorbing materials. Therefore, the paper conducted experiments under low speed/low load conditions to explore the EA characteristics of materials, providing a basis for further research on the application of high speed/high load environments [9].

2 Related works

Recently, various biomimetic design concepts have gradually attracted the attention of scientists and engineers, among which the SW structure, as a natural optimized structure, has been widely studied. The research on energy absorbing structure design of porous materials on the ground of SW biomimetic structures is rapidly developing. The literature describes methods for simulating structures in porous materials, such as fractal theory and pattern methods. It also explores the potential for structural optimization based on various biomimetic principles and methods. Meanwhile, introducing SW structures into porous material design is bound to bring innovative breakthroughs to various structural applications, such as automotive safety protection, building seismic resistance, and other fields [10].

In terms of manufacturing technology, some teams have made breakthroughs. For example, the NG team utilized biomimetic spinning technology to produce a water-soluble recombinant spider silk protein that can be assembled naturally, and spun it into silk using strain flow spinning. They spun under different fluid dynamics and chemical conditions, especially with the addition of acetonitrile and polyethylene glycol in the receiving bath. This study indicated that spinning conditions affected the mechanical properties of fibers, and adding acetonitrile and polyethylene glycol could increase the β-fold structure content of fibers, thereby improving their mechanical properties [11]. In addition, the Zhu's team used electrospinning technology to prepare SiO2 nanofiber membranes, and then prepared composite nanofiber membranes again. Through this ZIF-8@SiO2 composite membrane, the synergistic promotion effect of particulate matter capture and gaseous pollutant adsorption was effectively achieved, with a smoke removal efficiency of up to 99.96% [12].

At the application level, Zhang et al. designed a resistive pressure sensor on the ground of the structure of natural SW. The sensor combines different materials and exhibits characteristics similar to SW. It exhibits excellent adhesion on Polydimethylsiloxane and has a fast response time, capable of detecting pressure changes as low as 10 Pa. After undergoing 5000 cycles of pressure loading/unloading testing, the sensor still maintains stable performance without degradation, proving its potential application in electronic skin systems [13]. Weng et al. used design inspiration from SWs to create a multifunctional network structure of carbon nanotube polymer composites. This structure could be applied to multi response actuators, super-capacitors, and electromagnetic interference shielding devices to achieve non-interference between execution and energy storage functions [14]. This showed that the bionic design method on the ground of SW structure was not only limited to theory and experiment, but also

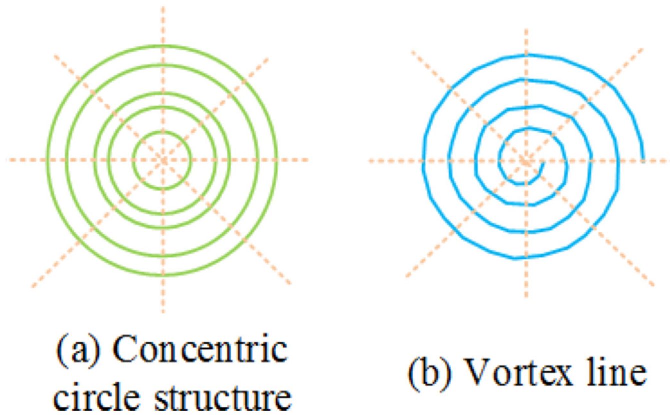


Fig. 1. SW structure.

involved many fields such as the preparation of new materials, performance testing and computational simulation. For example, porous hybrid materials, biological materials, air gel, etc. were all exploring the advantages and limitations of SW structure in practice.

In summary, the design and research of porous material energy absorbing structures on the ground of SW biomimetic structures have achieved certain results and shown good development prospects. However, the application of SW structures in the study of energy absorbing materials is still quite rare. Therefore, using SW structures to propose new porous material design schemes provides important theoretical support and practical guidance for further improving the performance of energy absorbing structures.

3 Porous material energy absorbing structure on the ground of SW biomimetic structure

The SW structure, as one of the structures with astonishing elasticity in nature, can be regarded as a symbol of both stability and elasticity. As an energy absorbing structure, it effectively reduces impact force and stabilizes pressure, increasing material protection and durability. Through biomimetic analysis of the SW structure, this study designs a porous material with significant EA properties. This material relies on its complex and unique network structure, which twists and contracts while withstanding impact forces to dissipate energy and avoid direct structural damage [15–17]. Not only that, this structure also provides a high degree of elasticity and resilience for this material, making it have a longer service life and higher durability in the application process.

3.1 SW structure

An in-depth exploration of the evolution process of SW structure reveals that it can be divided into three key stages: stuttering, patchy web, and circular web. In these three stages, the circular web, with its concise and regular structure, becomes a landmark stage in the evolution of SWs. On the ground of this importance, research on the structure of SWs focuses on the circular web form [18–20]. The common structure of SWs is shown in Figure 1.

At present, there are roughly two main SW models studied, namely the concentric circular structure in Figure 1a and the spiral linear structure in Figure 1b. When the SW has a concentric circular structure, the length of the spider silk can be calculated by formula (1).

$$L_1 = \frac{k(2\pi r + 2k\pi r)}{2}. \tag{1}$$

In formula (1), k is the number of concentric SWs, with the minimum circle radius and the difference in center radii between adjacent circles being r. Therefore, the efficiency of a SW is the ratio of the maximum coverage area of a concentric web to the length of the spider silk, which can be calculated by formula (2).

$$C_1 = \frac{\pi k^2 r^2}{\frac{k(2\pi r + 2k\pi r)}{2}} = \frac{kr}{k+1}. \tag{2}$$

In formula (2), C_1 is the efficiency of the concentric SW. When the SW structure is a vortex shaped structure, the calculation formula is represented by formula (3) because the helix is not a standard circle.

$$L_2 = \int_0^{2k\pi} \left(j^2(\theta) + j^2\right)^{\frac{1}{2}} d\theta = \frac{\sqrt{a^2 + \alpha^2 a^2}}{a}\left(e^{2k\pi\alpha} - 1\right). \tag{3}$$

In formula (3), j is the polar diameter. θ is the polar angle. α and α are the constant. Therefore, the coverage area of the spiral SW can be expressed by formula (4).

$$S_2 = \frac{1}{2}\int_0^{2k\pi} \left(ae^{\theta\alpha}\right)^2 d\theta. \tag{4}$$

In formula (4), α is a constant. The efficiency of the spiral web is the ratio of the covered area to the length of the helix. After solving the mathematical equation of equal efficiency conditions, when the concentric circle or vortex coil is 17, the spiral and concentric circle SW can achieve

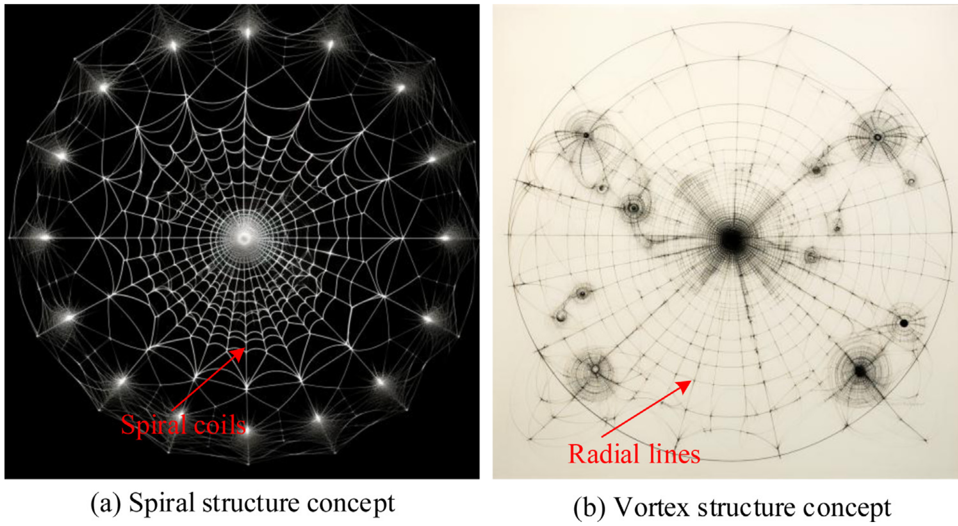


Fig. 2. SW structure concept diagram.

the same efficiency. As the number of turns increases, the SW of the scroll line exhibits higher efficiency. Therefore, the use of a vortex structure can reduce more glandular filament consumption while capturing the same number of insects, that is, the lattice structure has more circles, which has a better EA effect. Similarly, due to the fewer connection points of spiral SWs than concentric circles, their weaving speed has also been improved [21–23]. Therefore, in this study, spiral lines are chosen to simulate logarithmic spiral lines to draw a more realistic SW model, while simplifying the modeling process, as shown in Figure 2.

The quantity of radial lines (QRLs) and spiral coils of a SW is an important characteristic that affects its strength and determines the overall structure of the web. The diameter and quantity of spiral coils of SW can help optimize the structure of porous materials, improve their EA performance, enhance their EA and dispersion ability under impact, and ensure their structural stability. In addition, simulating the SW structure to increase the QRLs and optimize the quantity of spiral coils can effectively enhance the strength and toughness of materials, and improve their impact and fatigue resistance. In fact, the maximum capture area of a SW and the impact force of insects directly affect these two parameters. Increasing the QRLs helps to improve the strength of the mesh, while increasing the quantity of spiral coils helps to disperse more energy during impact. In addition, when the radial bearing capacity is increased, the required QRLs will decrease, and the spiral line will also decrease. Therefore, given the net area and insect impact force, the radial bearing capacity and spiral adhesion force will directly affect the selection of these two parameters. In a biomimetic model, the cross-sectional area of the SW's radial and helical lines can be adjusted to study the absorption effect of different radial and helical coil numbers on impact energy. Therefore, after determining the QRLes of the spiral coil, the quantity of spiral coils can be represented by formula (5).

$$n = \frac{RF}{2sf}. \tag{5}$$

In formula (5), F is the force to break free from the SW, f is the maximum adhesion force, R is the maximum area, and s is the cross-sectional area of the energy absorbing body.

3.2 Energy absorbing structure for SW biomimetic materials

When designing biomimetic web materials, a lattice structure is created by determining the web structure and studying the characteristics of the diameter and spiral lines, as shown in Figure 3.

In this structure in Figure 3d, the red line represents the radial structure, while the blue line represents the helix structure. By designing the diameters into the same rotation form as the helix, and combining the diameters and the helix in opposite directions, the rotation angle is consistent to ensure the symmetry of the lattice structure. The composite bionic SW lattice structure shown in Figure 3e is created by fusing the simple bionic web lattice with the diameter structure of the spiral bionic web lattice through further research. This structure retains the characteristics of the simple SW diameter in the center, and integrates the elements of the spiral bionic SW diameter at both ends. In addition, according to the optimization and analysis of the spider structure, it can be found that the radial structure is significantly superior to other structures in terms of EA effect, as shown in Figures 3a–c. When designing the basic bionic SW structure, the longitudinal material optimization of lattice structure should be given priority. At the same time, the key feature of the lattice, porosity, is considered.

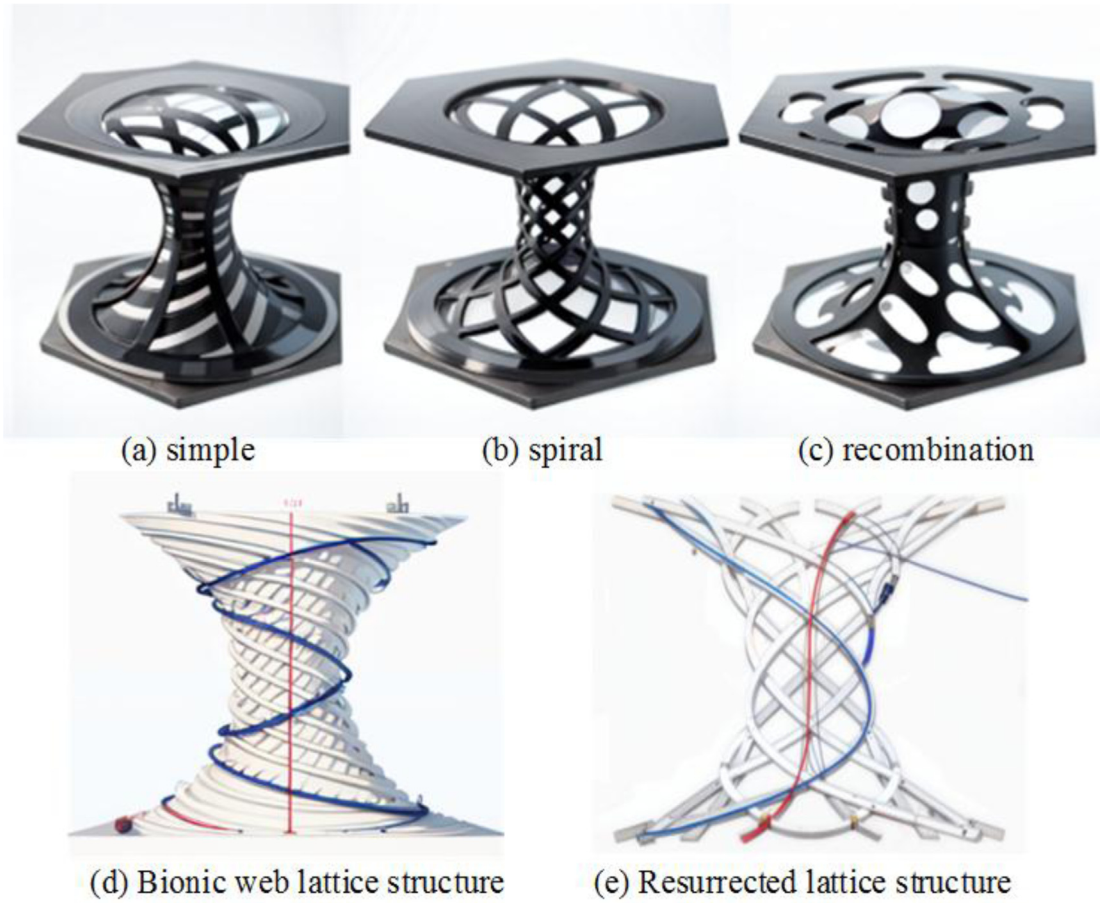


Fig. 3. Bionic web lattice structure.

Porosity is a crucial characteristic of the lattice structure. In Figure 4, “relative yield” refers to the strength of the biomimetic structure before it permanently deforms under a specific pressure or external force, while “relative elastic” describes the structure’s ability to return to its original state after compression or stretching. These two parameters are key indicators for evaluating the stability and resilience of biomimetic materials when they are subjected to external forces on the basis of simulating natural structures. The radial length can be calculated using formula (6)

$$L_3 = \int_n^m \sqrt{[f'(x)]^2 + 1}dx. \tag{6}$$

In formula (6), m and n are the horizontal coordinates of the endpoints in the lattice structure, and $f(x)$ is the radial structure. Therefore, the length of the helix can be represented by formula (7).

$$L_2 = \frac{\pi n f(x)}{\cos\beta}. \tag{7}$$

In formula (7), β is the rising angle of the helix, and n is the number of coils. The volume of lattice structure units can be expressed by formula (8).

$$V_1 = S_1 L_1 N_1 + S_2 L_2 N_2. \tag{8}$$

In formula (8), S_1 is the cross-sectional area of the radial line, S_2 is the cross-sectional area of the spiral line, N is the QRLs, and N_2 is the quantity of spiral lines (QSL). Therefore, the space occupied by structural units can be represented by formula (9).

$$V_2 = \pi \int_a^b f^2(x)dx. \tag{9}$$

The lattice porosity is the ratio of formula (8) to formula (9).

$$\rho = \frac{V_1}{V_2}. \tag{10}$$

In formula (10), ρ is the lattice porosity. When the biomimetic structure absorbs energy, it first enters the elastic stage. Therefore, when subjected to vertical compression, the projection area of the biomimetic structure in the vertical stage can be calculated by formula (11).

$$S_z = \pi^2 \left[[f(a)]^2 - \left[f\left(\frac{b-a}{2} \right) \right]^2 \right]. \tag{11}$$

When under compression, the overall force area can be expressed by formula (12).

$$S_x = \pi f(a)^2. \tag{12}$$

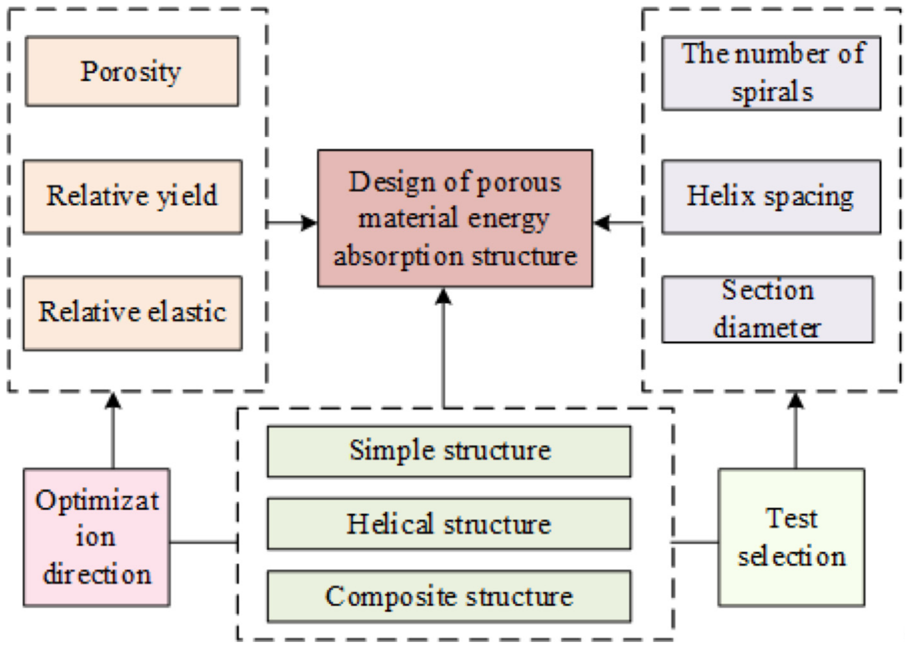


Fig. 4. Bionic structure simulation.

Therefore, the relative elastic modulus of biomimetic structures in the vertical direction can be expressed by formula (13).

$$E_g = \frac{S_z}{S_x} E_t. \tag{13}$$

In formula (13), E_t is the elastic modulus of the biomimetic structure matrix. The relative yield strength of biomimetic structures can be calculated by formula (14).

$$\sigma_a = \frac{S_z}{S_x} \sigma_t. \tag{14}$$

In formula (14), σ_t is the yield strength of the biomimetic structure matrix. The EA effect can be expressed by formula (15).

$$E_a = \int_0^d c(s) ds. \tag{15}$$

In formula (15), d is the collision displacement of the biomimetic structure, and $c(s)$ is the strain force curve. The peak stress is the maximum equivalent stress at which the biomimetic structure absorbs energy during impact, and the specific energy absorption (SEA) is the EA efficiency, which can be expressed by formula (16).

$$SEA = \frac{E_a}{m}. \tag{16}$$

In formula (16), m is the mass. The calculation formula of peak stress is shown in formula (17).

$$\tau_{\max} = 1.5\frac{V}{A} = \frac{V}{lh}. \tag{17}$$

Table 1. A table of abbreviations.

Abbreviation	Definition
Spider web	SW
Quantity of radial lines	QRL
Quantity of spiral lines	QSL
Energy absorption	EA
Specific energy absorption	SEA

In formula (17), V is the shear force of the section, A is the area of the section, l is the width of the section and h is the height of the section.

The list of research abbreviations is shown in Table 1. Table 1 shows the acronyms used in this study and their definitions, covering key parameters of SW structure and energy absorbing materials.

4 Experiment about energy absorbing structure of biomimetic porous materials with SW structure

This study evaluates and compares three optimized porous energy absorbing structures for low-speed impact testing – spiral biomimetic energy absorbing structures, simple biomimetic energy absorbing structures, and composite biomimetic energy absorbing structures. It explores the total EA of these energy absorbing structures under different impact energies and their sensitivity to different design parameters. On the ground of experimental data, it is necessary to identify and develop more effective design strategies and process parameters.

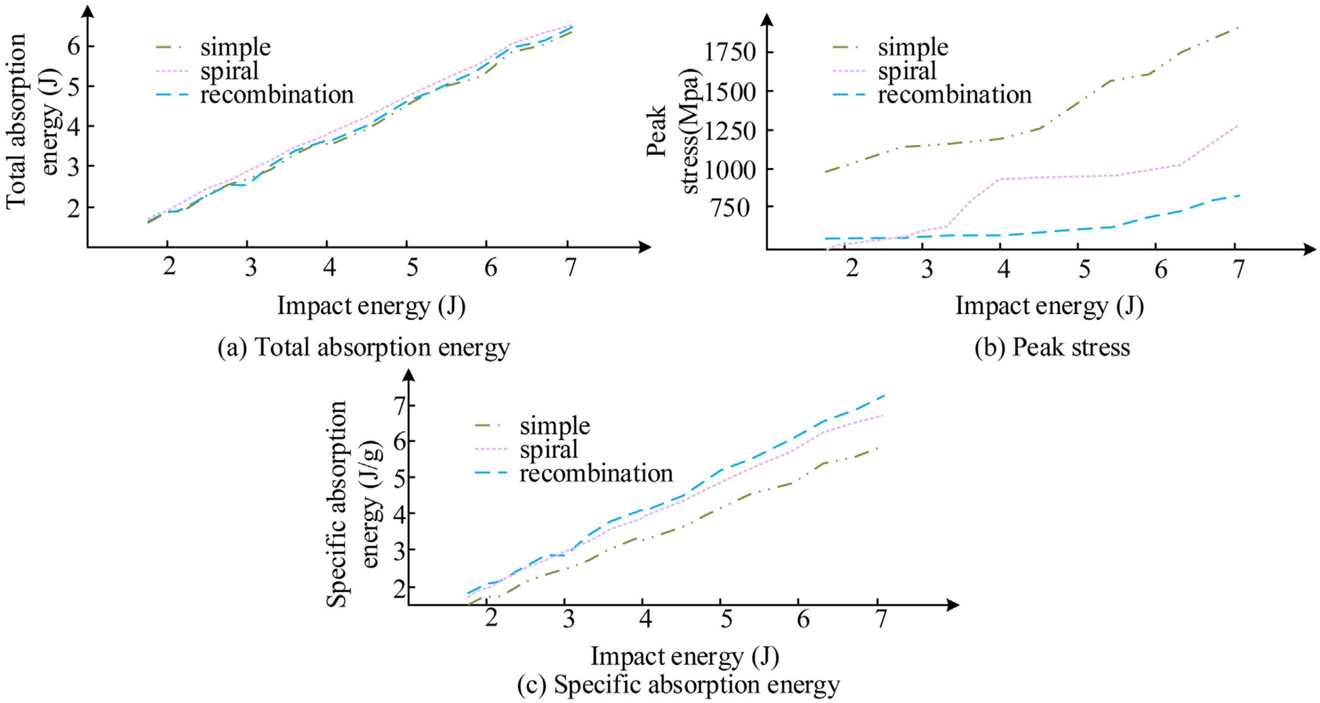


Fig. 5. Comparison of energy absorption effect.

4.1 Energy absorption effect of porous material energy absorbing structure

It analyzes the EA effects of three different EA structures on the ground of experimental optimization. This study conducts low-speed impact EA simulation experiments on three optimized biomimetic EA structures. They are spiral biomimetic energy absorbing structures, simple biomimetic energy absorbing structures, and composite biomimetic energy absorbing structures, with aluminum alloy as the substrate material. It evaluates the total EA of three different biomimetic energy absorbing structures under different impact energies. In the part of impact experiment, five samples are used in each experimental group to ensure the reliability and statistical significance of the data. Experimental data is captured using a high-speed camera system and force sensors to monitor the sample's response during impact in real time. The EA efficiency, peak stress and deformation behavior are recorded by applying different energy levels to the samples. Data analysis is performed using specialized software to ensure accurate calculations of parameters such as total EA, SEA and peak stress to assess the impact of different structural designs on EA performance.

Figure 5 shows the comparison of EA effects in different directions, and Figure 5a shows the total EA of the structure under low impact force. This indicates that the spiral structure possesses the most excellent EA effect. When the impact force reaches 7J, the total absorbed energy is over 90%. This is slightly lower than the proportion of total absorbed energy in simple biomimetic structures, which is within 85%–90%. Therefore, the natural EA characteristics of different energy absorbing structures are excellent overall. The peak stress changes under different impact energies in Figure 5b. The results shows that the peak stress of the simple biomimetic structure is relatively the highest, while the other two structures are more effective in reducing peak stress. From this perspective, the design of composite energy absorbing structures demonstrates outstanding superiority. Finally, under different impact energies in Figure 7c, the composite biomimetic structure outperforms the other two in terms of performance, with ordinary and spiral biomimetic SWs exhibiting lower EA. Among them, a mirror impact force analysis is conducted on the EA performance of a simple biomimetic structure, and the experimental results are shown in Table 2.

As shown in Table 2, the influence of different impact conditions on typical EA performance at low speed and low load is studied, and the variation trend of relevant parameters is further discussed. The experimental results show that under lower impact force conditions (such as 5J), the EA is 50 mJ, the EA efficiency is 10 mJ/g, the peak stress is 30 MPa, and the total EA is 500mJ. With the increase of impact force, the performance shows significant improvement. When reaching 20J, the EA increases to 200 mJ, the EA efficiency is 40 mJ/g, the peak stress further increases to 70 MPa, and the total EA is 2000 mJ.

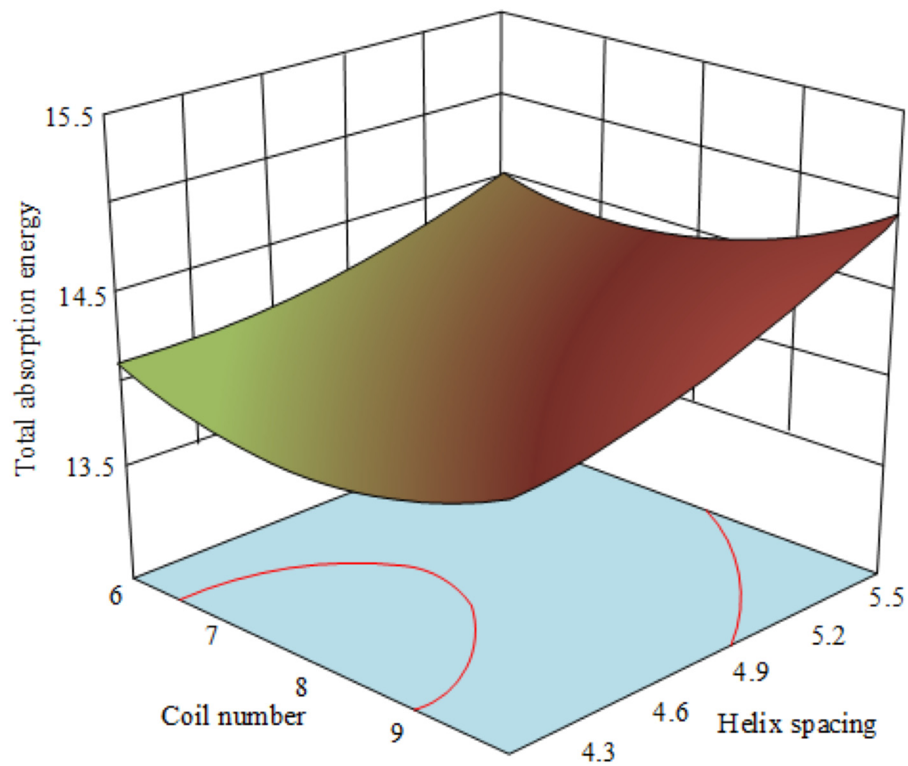


Fig. 6. Influence of different coil modes on total energy absorption.

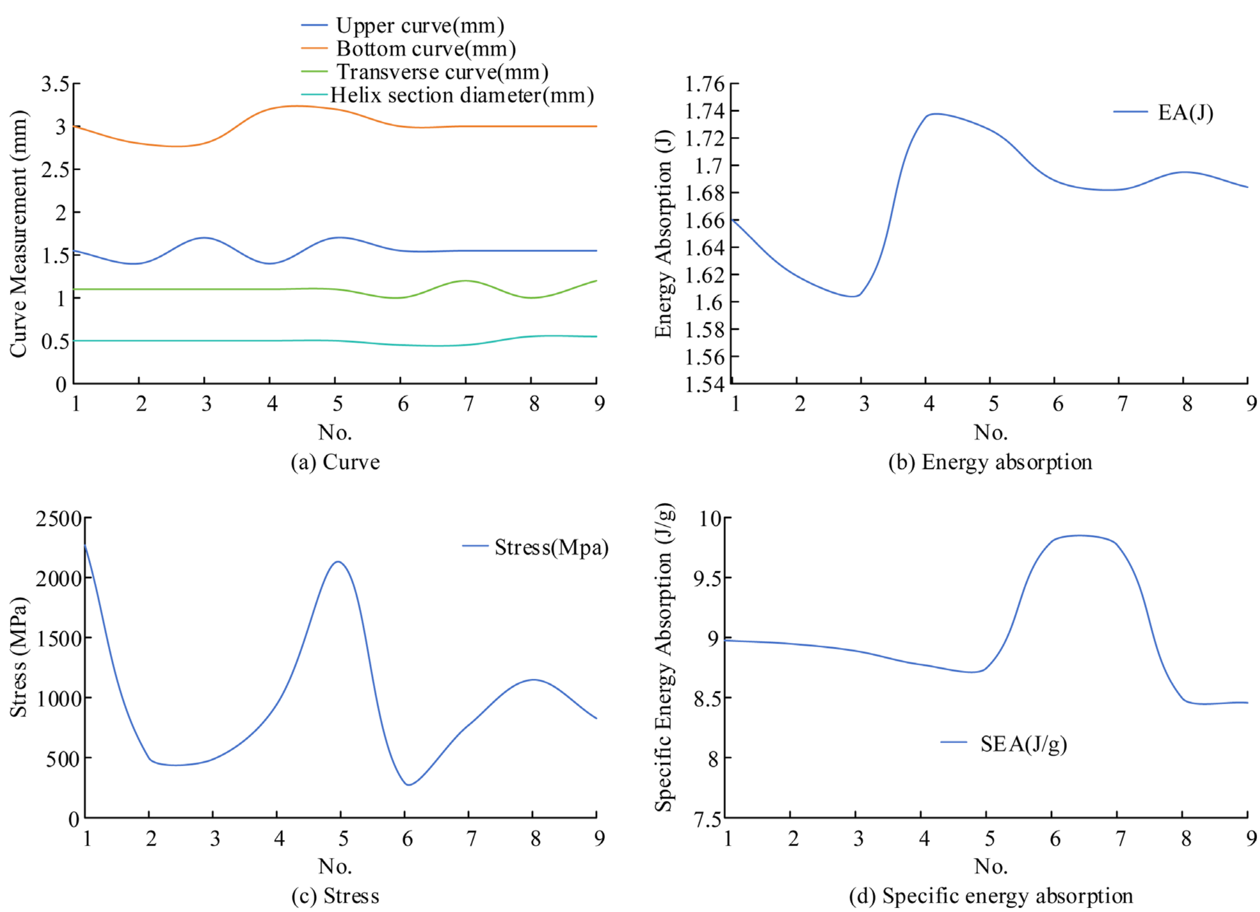


Fig. 7. Material performance characteristics under impact conditions.

Table 2. Effect of mirror impact force on energy absorption performance.

No.	Impact force (J)	Energy absorption (mJ)	Energy absorption efficiency (mJ/g)	Peak stress (MPa)	Total absorption energy (mJ)
1	5	50	10	30	500
2	7	70	14	35	700
3	10	100	20	45	1000
4	12	120	24	48	1200
5	15	150	30	60	1500
6	20	200	40	70	2000

Experimental data analysis shows that as the impact force increases, the EA, EA efficiency, and peak stress all improve. This indicates that under high impact forces, energy absorbing materials have stronger EA and dispersion capabilities, which are crucial for ensuring the safety and stability of the structure. Meanwhile, the improvement of EA efficiency helps to further optimize the design of EA structures and improve their effectiveness and performance in practical applications. When analyzing experimental data, other factors need to be considered, such as the materials used, porosity, and structure, which may have a significant impact on various parameters. Figure 6 shows the effect of the number and spacing of coils on the total EA in a simple energy absorbing structure.

Figure 6 shows that the total EA of a simple biomimetic energy absorbing structure increases with the increase of the quantity of spiral coils and the spacing between spiral lines. When the central area of the energy absorbing structure is impacted, the strain generated by the spiral line farther from the core area will be greater. Increasing the number and spacing of spiral coils can expand the distance between the spiral and the core area of the SW, thereby increasing the strain of the spiral during the impact process. This can further improve the EA of biomimetic structures.

4.2 Experimental analysis and comparison of biomimetic energy absorbing structures

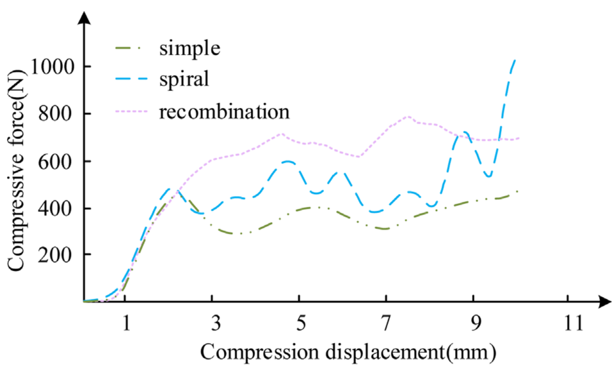
Through experimental data analysis of composite biomimetic energy absorbing structures, this study explores the influence of various parameter combinations on the EA effect of porous materials. Then, this study verifies that the biomimetic structure maintains good EA performance even after parameter optimization, and delves into the significant influence of the cross-sectional diameter of the helix on the EA effect.

Figure 7 shows the experimental results of a composite biomimetic energy absorbing structure, where the radial cross-sectional diameter of the structure is 0.5 mm. After testing various parameter combinations, it is clear that altering certain parameters does impact the EA capability of porous materials. When the cross-sectional diameters of the upper, lower, and helical curves are all 1.55 mm, 3 mm, and 0.5 mm, the total absorbed energy is 1.66J, the peak stress is 2269.688 Mpa, and the specific absorbed energy is 8.975 J/g. However, after changing the parameters to 1.7 mm, 3.2 mm, and 0.5 mm, although the total absorbed energy and peak stress slightly decreases, the comparative absorbed energy remains at 8.744 J/g. This proves that even with parameter optimization, biomimetic structures still maintain good EA performance. Overall, increasing the upper and lower curves, as well as the cross-sectional diameter of the spiral, can maintain or improve EA, but it does not have a significant impact on the overall EA effect. Meanwhile, the adjustment of the cross-sectional diameter of the spiral has a significant impact on the EA effect. For example, when the cross-sectional diameter of the helix increases from 0.45 mm to 0.55 mm, the total absorbed energy slightly increases, the peak stress significantly increases, and the specific absorbed energy actually decreases. The above analysis indicates that biomimetic structural models have a significant impact on the final design of energy absorbing structures. In the experiment, multiple possibilities are considered and it is found that even with changes in parameters, the composite energy absorbing structure still has good EA effects.

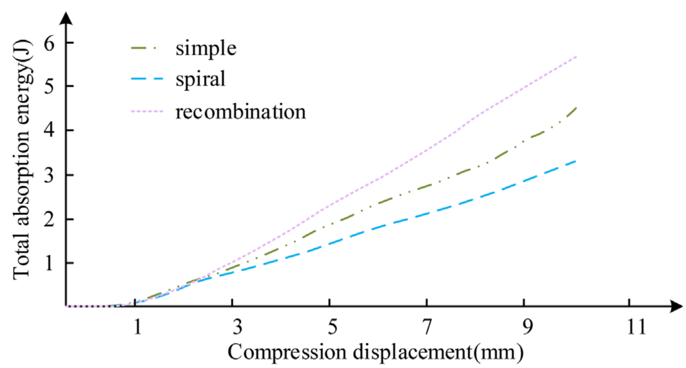
Table 3 shows the effects of different cross-sectional diameters and radial cross-sectional areas of helical wires on the performance of helical biomimetic energy absorbing structures in the experiment. Z1 to Z4 are cases where the helix rotation angle is 360 degrees, and B1 to B9 are cases where the helix rotation angle is 540 degrees. When the rotation angle is 360 degrees (Z1-Z4), changes in the cross-sectional diameter of the spiral and the cross-sectional area of the radial will have a certain impact on the EA effect. Reducing the cross-sectional diameter of the spiral from 0.55 mm to 0.45 mm will significantly decrease the EA effect. Similarly, when the cross-sectional area of the radial line changes from 0.5 to 0.45, the EA effect also decreases. Secondly, at a 540 degree rotation angle, it exhibits a similar trend to a 360 degree rotation angle. Reducing the cross-sectional diameter of the spiral from 0.55 mm to 0.45 mm also leads to a decrease in EA efficiency, as shown in the data of B1, B6, and B7. Meanwhile, when the cross-sectional area of the radial line changes from 0.5 to 0.55 or 0.45, the EA effect will also be affected, as shown in the data of B1, B6, and B8. The data analysis in Table 3 shows that under different rotation angles, the changes in the cross-sectional diameter and radial cross-sectional area of the spiral have a significant impact on the EA effect of the spiral biomimetic energy absorbing structure.

Table 3. Experimental results of complex energy-absorbing structure.

No.	Helix section diameter	Radial section area	EA (J)	Stress (Mpa)	SEA (J/g)
Z1	0.55	0.5	1.775	2335.692	8.736
Z2	0.5	0.55	1.765	2408.214	8.684
Z3	0.45	0.5	1.59	4318.021	7.789
Z4	0.5	0.45	1.644	4546.091	8.066
B1	0.5	0.5	1.73	1492.326	6.069
B2	0.5	0.5	1.73	1492.326	6.069
B3	0.5	0.5	1.73	1492.326	6.069
B4	0.5	0.5	1.73	1492.326	6.069
B5	0.5	0.5	1.73	1492.326	6.069
B6	0.45	0.55	1.755	1083.075	8.629
B7	0.55	0.55	1.785	676.457	6.265
B8	0.55	0.45	1.76	1011.045	8.388
B9	0.45	0.45	1.688	2059.647	8.289



(a) Compression displacement curve



(b) Total absorbed energy and compressive displacement

Fig. 8. Spiral bionic energy absorption structure.

Figure 8a shows that the triggering force of the simple biomimetic structure exceeds 400N. When the compression displacement exceeds 10 mm, it does not enter the compaction stage and the EA level is poor. The triggering force of the spiral structure exceeds 480N, and the compression displacement is about 9 mm for compaction. The triggering force of the composite structure exceeds 700N, but the compression displacement is 10 mm without compaction. In Figure 8b, the composite structure exhibits excellent total EA performance. In the actual EA structure design process, the EA effect is better, and the worst is the simple biomimetic structure.

The EA response curve in Figure 9a shows that as the helix rotation angle, helix cross-sectional diameter, and radial cross-sectional diameter increase, the total EA of the spiral biomimetic energy absorbing structure shows an increasing trend. The stress response curve in Figure 9b shows that as the rotation angle of the spiral increases, the peak stress of the spiral biomimetic spider mesh array shows a trend of first decreasing and then increasing. The actual picture of relevant compaction is shown in Figure 10.

From the comparison of Figure 10a before compaction and Figure 10b after compaction, it can be seen that there is no compaction.

5 Conclusion

The SW structure has shown good application prospects in many fields due to its unique advantages. Porous materials designed through structural optimization will exhibit significant advantages in EA, impact damping, and other aspects. The paper aimed to introduce adaptive design on the ground of SW structure and construct a new porous material energy absorbing structure, thereby improving the energy absorbing material's resistance to impact energy. The results showed that by trying different SW structure parameters, the total absorbed energy exceeded 1.6J and the peak stress exceeded 2000 Mpa when the upper curve was 1.55 mm, the lower curve was 3 mm, and the spiral section diameter was 0.5 mm. Its specific absorption energy was 8.975 J/g. When the structural parameters of the SW diameter line were changed to 1.7 mm, 3.2 mm, and

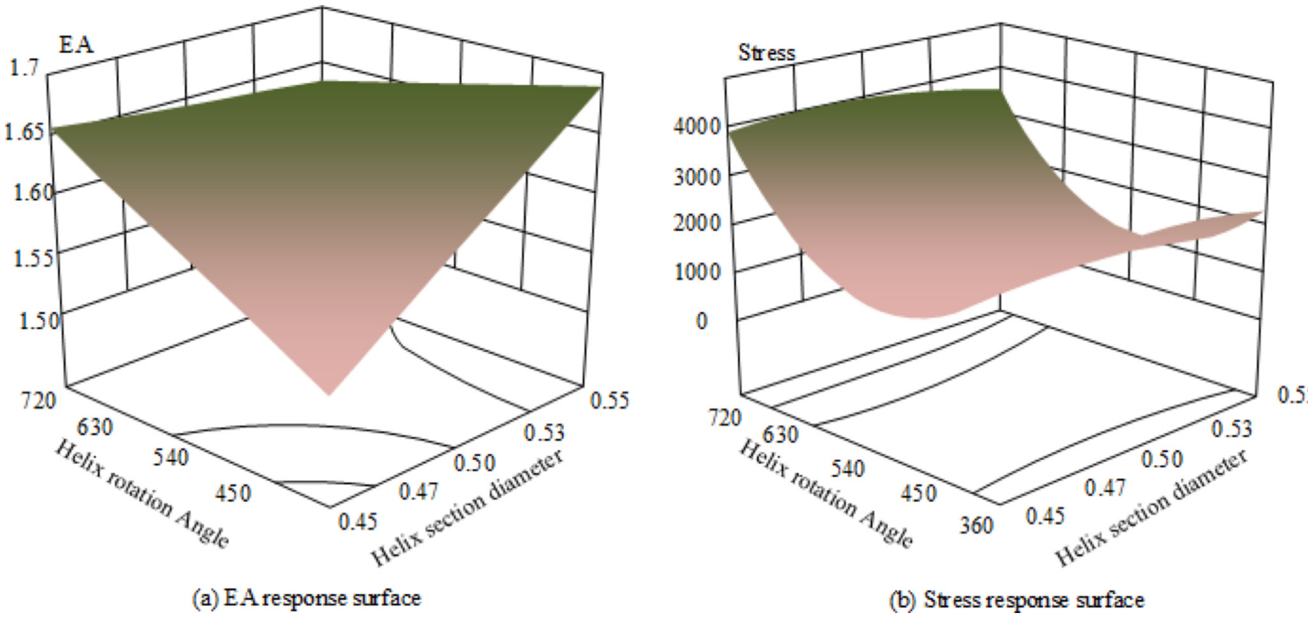
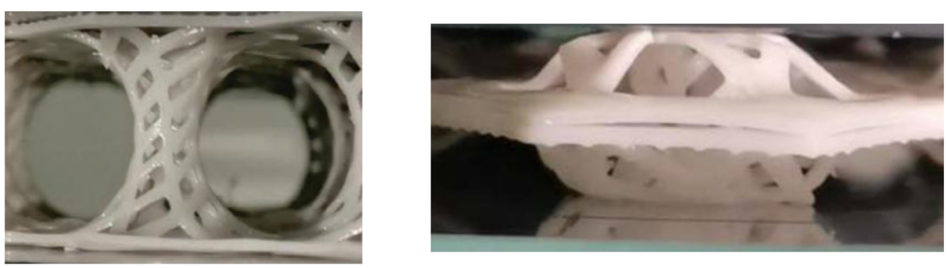


Fig. 9. Response surface effect.



(a) Precompression (b) After compression

Fig. 10. Relevant compaction diagram.

0.5 mm, the SEA remained at 8.744 J/g. The cross-sectional area of the spiral had a significant impact on the EA effect. The rotation angle had little effect on the EA effect within a certain range. Among all biomimetic structures, the composite SW structure performed the best. In the low-speed impact test, it showed good performance in terms of total EA and peak stress under different impact energies. After being compressed by a static load of 700N, its total EA performance was superior. Overall, the biomimetic EA structure designed in this study performs excellently. Insufficient research is due to the need to explore issues such as producing materials that meet the expected precision requirements. Therefore, further exploration is needed in this area for future research.

Funding

The research is supported by the Young Doctor Research Initiation Fund Project of Harbin University (No. HUDF2023102).

Conflict of Interest

The authors declare no conflict of interests.

Data availability statement

All data generated or analysed during this study are included in this published article.

Author contribution statement

In the context of environmental protection and energy conservation, it is of great practical significance to study the design of porous material energy absorbing structures on the ground of spider web biomimetic structures. Deqiu Zhang collected the samples. Jingyan Wang analysed the data. Deqiu Zhang and Jingyan Wang conducted the experiments and analysed the results. All authors discussed the results and wrote the manuscript.

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Cite this article as: Deqiu Zhang, Jingyan Wang, Porous material energy absorbing structure based on spider web biomimetic structure, Manufacturing Rev. **11**, 12 (2024)