An overview of impact resistance of auxetic lattice structure

Xiufeng Huang*, Zhenhua Zhang* and Jihang Wu*

College of Naval Architecture & Ocean, Naval University of Engineering, Wuhan 430033, China

*Corresponding author e-mail: 2zsz@163.com, *xiufeng_hhu@126.com, bqvz859@163.com

Abstract. Auxetic materials have many advantages in strength and energy absorption, which have become a research focus of scholars at home and abroad. It’s of great significance to ship protection structure design that researching deeply on auxetic lattice structures. According to the unique properties of auxetic lattice structures, this paper mainly introduces the research status of the impact resistance mechanical properties of the new structure. The research status of low-speed impact, high-speed projectile impact, and explosion impact in the auxetic lattice structures is described from three aspects: theoretical, experimental and simulation studies. The research status of in-plane impact at medium and low velocities, explosive impact and projectile penetration is expounded. The effects of geometric parameters and impact velocity on deformation modes and energy absorption of structures are also analyzed. Finally, summarize the article and point out the contents in the future.

1. Introduction
With the continuous development of modern ships, the attack methods of weapons are becoming more advanced. As a large maritime structure, ships are vulnerable to risks and need effective protection. Therefore, it is more necessary to design a lightweight structure with good impact resistance and good energy absorption. At present, the lattice sandwich structure has been proven to withstand a certain explosive impact load, and its structure type has large design space. With the deepening of research on auxetic lattice structure, more new lattice structures are being designed. At the same time, people's research on lattice structure has gradually changed from the traditional two-dimensional structure to a three-dimensional structure with better mechanical properties, more reasonable structure and lighter weight. Obvious negative Poisson's ratio effect. The article starts with the special properties of the negative poisson's ratio lattice structure, expounds the research progress of the impact resistance performance of different configuration lattice structures, and looks forward to the future research directions.

2. Research on Mechanical Properties of Negative Poisson's Ratio Structure under Quasi-static Compression
When analyzing the static mechanical properties of a negative Poisson's ratio structure, an electronic universal testing machine is usually used to perform a quasi-static compression test to obtain the load-displacement curve. Fu [1] has used stereolithography technology to prepare chiral auxetic lattice structures for compression tests. His experimental and simulation results verify the correctness of the
theoretical formula. On this basis, researchers analyzed other types of auxetic lattice structures in detail. Wang [2] has studied a three-dimensional columnar auxetic lattice structure with a double arrow configuration as a unit. The auxetic lattice structure with special shape has obvious vibration effect and is regarded as spring, damping of the whole frame. According to the characteristics of the auxetic lattice structure under small deformation, we can know the role which is each component of the auxetic lattice structure.

Compression tests indicate that the number of layers, the height of the layers, and the number of units in each layer will affect the axial compression performance of the structure. Reducing the equivalent height of each layer and increasing the number of cells in each layer can improve the overall stiffness of the structure. When the relative density of the designed lattice structure is constant, increasing the inclination angle and thickness of the structural members can increase the bearing capacity of the structure, but at the same time, it will reduce the maximum strain.

3. Research on Impact Mechanical Properties of Negative Poisson's Ratio Structure

3.1. Medium-low speed impact
In the analysis of dynamic mechanical properties of impacts, the anti-collision structure of a vehicle or a ship is mainly used as an application object, and the protective performance of a part or a large part of the vehicle when it is subjected to low-speed impact or impact is studied. For auxetic lattice structures, the macroscopic stress-strain curve under the impact of in-plane and low-velocity impacts has two characteristic quantities: specific energy absorption and platform stress. The two characteristic quantities indicate the energy absorption effect of the structure [3] [4].

Impact response of typical negative Poisson's ratio lattice structure can be divided into three parts: elastic zone, platform zone and compaction zone. Initially, the stiffness of the model is large, and the structure undergoes elastic deformation. When the stress limit is reached, the stress-strain curve reaches a peak. When the impact is continued, the external members of the structure are crushed and collapsed, and the stress-strain curve suddenly drops, and then the stress-strain curve rises again because the upper structure of the model contacts the lower structure. The whole process is repeated, multiple peaks appear in the stress-strain curve and enter the plateau area. When the structure is completely crushed, the stress-strain curve slowly rises again and enters the compaction zone. The auxetic lattice structure with good energy absorption effect has a longer platform area, higher platform stress and larger specific energy absorption, and the platform area occupies most of the deformation.

In numerical simulation, Zhang [5] has used the finite element method to study the dynamic impact properties of negative Poisson's ratio open-cell aluminium foam, calculated the platform stress, specific energy absorption, and described the deformation mode of the structure. The results show that the platform stress and energy absorption of open-cell foam aluminium with the same relative density under impact load are smaller than that of traditional foam aluminium structure, and the deformation mode of open-cell foam material is different from that of traditional foam material. Open-cell foam is not suitable for absorbing energy under low-speed impact, but the greater the impact speed of this material, the more obvious the effect of negative Poisson's ratio. Ma Fangwu [6] has proposed a concave triangular negative Poisson's ratio material. By changing the concave angle of the sides of the triangle, LS-DYNA finite element software was used to specifically analyse the in-plane impact deformation and energy of the concave form and impact velocity. Meanwhile, the impact dynamic properties of the concave triangular material and the hexagonal honeycomb material were compared. Under the condition that the properties of the matrix material, the boundary conditions and the loading conditions are the same, as the impact speed increases, the concave triangular negative Poisson exhibits a stronger energy absorption capacity than the material. It can be seen from the numerical simulations of Fig2. (d) And (e) that the deformation amount of the triangular material is smaller than that of the hexagonal honeycomb material.
Figure 1. Deformation process of NPR foam model in the early stage [5]

(a) Concave triangles structure with negative Poisson’s ratio
(b) Schematic diagram of model
(c) Schematic diagram of impact loading
(d) Concave triangle structure
(e) Hexagonal honeycomb structure

Figure 2. Impact Deformation of negative Poisson's ratio lattice structures [6]
In terms of experimental research, the simulation of in-plane impact at medium-low speed mostly uses a drop hammer impact tester widely used at home and abroad. The principle of method is simple, the cost is low, and the technology is mature. It can well simulate the problem of medium-low speed impact. Chen Shangjun [7] has studied the anti-penetration behaviour of metal honeycomb sandwich panels under low-speed impact loads using a drop hammer impact test system. The test has obtained failure modes and force-displacement curves of honeycomb sandwich panels under the impact of flat, hemispherical and conical hammer heads. It is concluded that the metal honeycomb sandwich plate has the best resistance to the penetration of the hemispherical hammer head, the worst resistance to the penetration of the flat-head hammer head, and the metal honeycomb sandwich plate has the best resistance to the penetration of the conical hammer head. Flat-head and hemispherical hammers have poor penetration capabilities. The honeycomb sandwich structure with small negative Poisson's ratio has a good energy absorption effect, but the peak stress will be reduced.

3.2. High-Speed projectile impact

It is a relatively new research direction for the problem of ballistic penetration resistance of auxetic lattice structure. The auxetic lattice structure based on the principle of dense energy absorption under high-speed bomb impact is not suitable as a protective structure against high-speed local penetration impact. The traditional concave hexagonal negative Poisson's ratio honeycomb sandwich structure is capable of coping with high-speed or ultra-high-speed bullet penetration. The auxetic lattice structure does not have sufficient deformation time, and its protective performance is inferior to that of single-layer or double-layer boards. He Feixiang [8] used numerical simulation to study the impact resistance of foamed aluminum bullets on high-temperature nickel-based alloy honeycomb sandwich panels, and through comparison with experiments, he found that the high-temperature nickel-based alloy honeycomb sandwich panels had penetrating damage.
3.3. Explosion shock

For the explosion impact of the auxetic lattice structure, researchers mainly focused on the concave hexagonal honeycomb structure. This auxetic lattice structure is two-dimensional. The research of this structure started earlier and more mature. Through explosion experiments, the failure modes and energy absorption characteristics of honeycomb structures are studied, and numerical simulation is a more reliable research method that can fully understand the structural deformation process, dynamic response process and energy absorption analysis.

Li Junjie [9] has studied the impact resistance of rubber honeycomb cavity coverings with negative Poisson's ratio characteristics under underwater non-contact explosions. The results show that the stress concentration points in the coverings under shallow water explosions are located in a lattice. At the corners of the structural cell, a large amount of energy is dissipated during the complex stress waveform conversion process. The impact cover is in an underwater environment and is inevitably subject to hydrostatic pressure. Hydrostatic pressure will significantly reduce the ability of the water area outside the cover to form local cavitation, and more energy will enter the cover. The impact resistance of the recessed hexagonal honeycomb structure cover is also related to the structural parameters such as height, cell wall thickness and expansion angle. Yang Deqing [10] studied the geometric parameters (including cell wall thickness, cell layers, and Poisson's ratio) of concave hexagonal honeycomb sandwich structure with negative Poisson's ratio on underwater explosion resistance.
Yang Xiao tong [11] has studied the influence of honeycomb core layers of different base materials on the protection performance, and established a simulation analysis model under explosive impact load by Hyper mesh software. He compared the energy absorption ratio of the honeycomb structure backplane with different substrate materials, the kinetic energy characteristics of the backplane, and the maximum deformation of the backplane of the panel. The results show that the energy absorption of the honeycomb core layer accounts for about 50% - 60% of the whole. The H14 material has the best anti-explosion impact performance under the in-plane honeycomb structure, and the Q235 material has the best anti-explosion impact performance under the in-plane honeycomb structure.
Figure 6. Overall deformation cloud diagram of honeycomb structure under blast loading [10]

4. Conclusion

According to the above research progress, it can be seen that the special properties of the auxetic lattice structure have caused widespread concern of scholars. At present, the research on the lattice structure of the auxetic lattice structure mainly focuses on the proposal of new cell types, mechanical properties of lattice structure and optimization of negative Poisson's ratio performance. With the development of refined structure and the increase of complexity of geometric structure, if the auxetic ratio structure is developed into the main structure of protection and vibration isolation, some problems still need to be solved urgently:

(1) Stiffness issues. The lattice structure is a porous structure, and its low relative density results in insufficient stiffness under pressure. Since the auxetic lattice structure is more optimally recessed than the structural configuration, it tends to produce shrinkage deformation under compression, so the geometric configuration will also affect the stiffness. For how to increase the stiffness of the auxetic lattice structure so that it has a higher bearing capacity.

(2) Impact resistance. Compared with the auxetic ratio lattice structure, the impact resistance of the auxetic lattice structure is generally reflected in its stiffness enhancement effect when subjected to the impact of a rigid plate and the explosion shock wave, resulting in higher platform stress, which in turn attracts higher energy. For projectile penetration, due to the high impact velocity of the projectile, the stiffness enhancement effect of the auxetic lattice structure cannot be reflected, so its impact resistance is inferior to that of a single-layer plate. Therefore, a material with elastic, superplastic or non-newtonian fluid properties can be filled in the auxetic lattice sandwich structure to resist high-speed bullet penetration.

(3) Optimize design methods. By changing the geometric parameters of the cell structure, the mechanical properties of the structure can be improved. The reasonable design of the geometric parameters of the auxetic lattice structure is very important to improve its impact resistance. For structures with multiple configurations, researchers often use numerical simulation methods to find the optimal design scheme under specific working conditions, and a complete set of optimization design methods has not yet been formed.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51879270).
References

[1] Fu M, Liu F, Hu L. A novel category of 3D chiral material with negative Poisson’s ratio [J]. Composites Science & Technology, 2018.

[2] Wang Y, Wang L, Zhengdong, et al. Parametric analysis of a cylindrical negative Poisson’s ratio structure [J]. Smart Materials & Structures, 2016, 25(3): 035038.

[3] Gibson L J, Ashby M F. Ashby M. Cellular Solids: Structure and Properties 2nd ed [M]. Cambridge University Press, Cambridge, UK, 1999.

[4] Kooistra G W, Deshpande V S, Wadley H N G. Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium [J]. Acta Materialia, 2004, 52 (14): 4229 - 4237.

[5] Peiwen Zhang, Zhihua Wang, Longmao Zhao. Dynamic crushing behavior of open-cell aluminum foam with negative Poisson’s ratio [J]. Applied Physics A, 2017, 123 (5).

[6] Fangwu Ma, Hongyu Liang, Ying Zhao, et al. In-plane impact dynamic performance of concave triangle material with negative Poisson’s ratio [J]. Journal of Vibration and Shock, 2019, 38 (17): 81 - 87+127.

[7] Shangjun Chen, Qinghua Qin, Wei Zhang, et al. Experimental investigation on against penetration of metallic honeycomb sandwich plates under low-velocity impact [J]. Acta Aeronautica et Astronautica Sinica, 2018, 39 (02): 162 - 168.

[8] Feixiang He. Numerical simulation on the high-speed penetration resistance of porous metal sandwich structure [D]. Harbin Engineering University, 2013.

[9] Junjie Li, Meng Tao, Hanfeng Ye, et al. Anti-shock performance of honeycomb claddings with negative Poisson’s ratio subjected to UNDEX [J]. Journal of Vibration and Shock, 2019, 38 (21): 126 - 132.

[10] Deqing Yang, Xiangwen Zhang, Binghong Wu. The influence factors of explosion and shock resistance performance of auxetic sandwich defensive structures [J]. Journal of Shanghai Jiao Tong University, 2018, 52 (04): 379 - 387.

[11] Xiaotong Yang, Yunbo Zhou, Peng Li, et al. Analysis of the influence of matrix materials on the anti-explosion impact performance of honeycomb structure [J]. Science Technology and Engineering, 2019, 19 (29): 16 - 20.