

Research Progress of Lattice Shell Structure based on Kagome

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Abstract: The composite material shell structure has the characteristics of light weight, high strength and wide application scenarios, and has been widely used in the aerospace field in recent years. This paper first summarizes the structure, preparation process and mechanical properties of Kagome; secondly, discusses the preparation process, improvement and development of the lattice shell structure and mechanical properties in detail; finally, the application outlook and development direction of the material are forecasted.

Keywords: Kagome, Lattice Shell structures, Composite materials, Aerospace.

1. Introduction

In recent years, China's aerospace industry has made great development: from the completion of the Tiangong space station to the planned manned lunar landing before 2030... These have put forward new requirements for the carrying capacity of my country's aerospace vehicles.

Since the invention of fiber composite materials in the last century, they have been widely used in various aerospace structures due to their advantages of high strength, fatigue resistance and corrosion resistance, especially carbon fiber reinforced composite materials, which have light weight and high strength. In addition, new mechanical structures that have emerged in recent years have also further developed the mechanical properties of materials, providing design space for lightweight design, such as grid structures, reinforced structures, and sandwich structures.

Aiming at the problem of "how to reduce the weight of aerospace vehicles", many scientists and their teams have done related research. Many scientists have improved the original materials to achieve better performance. Deng et al. developed a resin formula for wet winding molding of carbon fiber composites with good viscosity temperature and viscosity properties, the material fully meets the wet winding molding process requirements of large-scale solid rocket motor casings [1]. At the same time, the new composite lightweight structure can also form a curved shell structure to meet various structural requirements in aerospace engineering, so it has received extensive attention and research in recent years.

This paper focuses on the overview of composite shell structures. Firstly, starting from Kagome, its structure and mechanical properties are discussed. Secondly, the shell structures designed based on Kagome structure in recent years are summarized, and the preparation process, structural design and mechanical properties are discussed. Finally, the development of the shell structure is summarized and forecasted, and the future development tendency is discussed.

2. Kagome Structure

The Kagome configuration is an significant part of the shell structure. The development history of the shell structure is actually the history of the continuous application and development of the kagome configuration.

2.1. Structure

The Kagome structure is a 3D- structure made of staggered hexagonal networks. The Kagome structure is named after Kagome, a traditional Japanese fine knitted fabric, which is one of the most representative patterns in traditional Japanese styles.

The hexagonal network of the Kagome structure consists of four joined hexagons, each with three sides, a central point, and a space with only one side, forming a hexagonal cavity. There is a joint position between each hexagon, which forms a Kagome structure. This structure has three distinct layers: the outermost hexagonal network, the middle hexagonal network, and the inner hexagonal network.

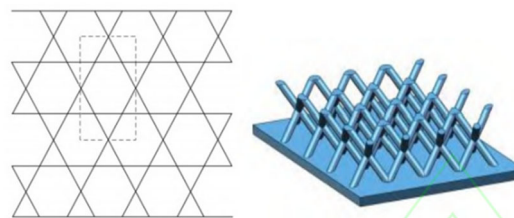


Figure 1. 2D- and 3D- Kagome structure

2.2. Mechanical properties

The Kagome lattice sandwich structure is a new kind of lattice sandwich structure with great mechanical properties proposed in recent years. Compared with tetrahedral and pyramidal lattice core structures, the 3D- Kagome core structure has higher strength and better buckling resistance, while exhibiting better isotropic properties.

In recent years, scientific researchers have carried out comprehensive research on the mechanical properties of Kagome by using experiments and theoretical models.

In terms of models, Pei et al. used Solidworks software to establish a finite element model, and conducted simulation experiments under specific parameters [2]. Pei et al. pointed out that for the Kagome sandwich structure, the places where the force deformation is most obvious during the compression process are the cross connections of the rods and the connection between the rods and the upper and lower panels [2]. This region is the place where the stress concentrates during the flat compression process. This is because under the action of vertical load, the rod in this region is twisted due to the shear force, which leads to the bending deformation of the rod(as shown in Figure 2).

In terms of experimentation, Zhu et al. selected isotropic and commonly used anisotropic Kagome honeycomb structures for crush resistance experiments [3]. The experimental results show that the isotropic Kagome honeycomb structure has better mechanical properties and mechanical load-bearing properties. Pei et al. used the 3D printing fused deposition process to prepare the Kagome sandwich structure of chopped carbon fiber/nylon composite material, and conducted a flat compression test on it with reference to the ASTM C365/C365M standard [2]. By changing the three parameters of diameter, core height and angle, The bearing capacity of the model is tested, and the results show that: with the increase of the diameter of the rod, the peak load increases, and the change of the diameter of the rod has a great influence on the amplitude of the peak load. However, the change of the core height and rod angle has little effect on the peak load, and the peak load increases with the decrease of the core height and the increase of the rod angle(as shown in Figure 3).

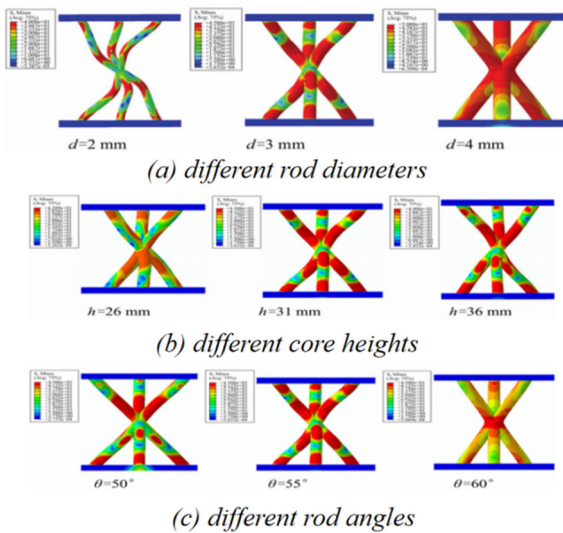


Figure 2. Finite element simulation stress diagrams with different parameters

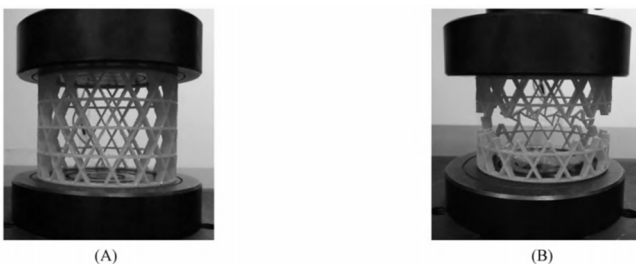


Figure 3. Schematic diagram of specimen a before(A) and after(B) experiment of Zhu et al.

It can be seen from the above that the Kagome configuration has high degrees of freedom, strong bearing capacity and better buckling resistance, so the sandwich shell structure designed based on the Kagome structure has good mechanical properties and a wide range of applications prospects, which will be discussed in detail later.

3. Lattice Shell Structure

We start with the 2D-Kagome structure. The grid shell structure is a lightweight structure with extremely high mass efficiency, which is currently widely used in the aerospace field.

3.1. Structure and Preparation

The grid shell structures mainly include triangles, Kagome shapes and so on. The grid shell structure is mainly made by the fiber winding process. In recent years, with the development of manufacturing technologies such as automatic winding, automation has been gradually realized. Filament winding is mainly divided into two steps: first, the continuous fiber soaked in resin glue is wound onto a mold with grooves, after that, the mold is removed by heating, forming and curing, and a grid shell structure is obtained.

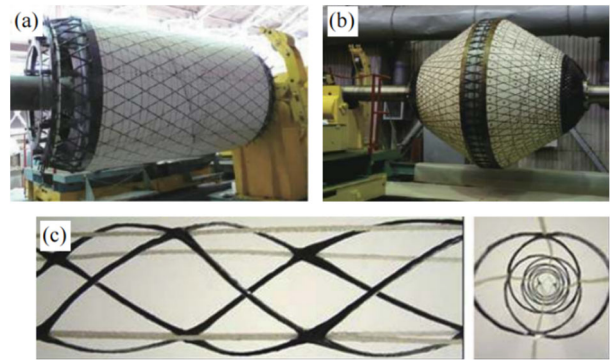


Figure 4. Fabrication process of grid cylinder

The grid structure is an open structure. Compared with other shell structures, the internal damage of the grid shell structure is easier to be detected and repaired, and it is not easily affected by moisture. At the same time, due to its unique preparation process, there are the following problems: Firstly, during the laying process of continuous fibers, there is fiber overlap at the intersection, which makes the mechanical properties of the ribs far lower than other composite material structures. Secondly, the ribs are in direct contact with the mold, and there is inevitably initial damage during the demoulding process [4].

3.2. Development and Improvement

After decades of development, scientists have improved the three problems mentioned above, which largely solved the existing problems and made the shell structure widely used in the aerospace field.

In order to reduce the accumulation and overhead of continuous fibers at the intersection, the Kagome configuration can be used, that is, for the intersection where three or more fibers pass through, the ribs are offset upwards (as shown in Figure 5(a)). However, by adjusting the process parameters in the fiber winding process, the effect on increasing the fiber content is extremely limited. Therefore, under the premise of using the Kagome configuration, improving all aspects of the winding process has always been

the focus of scientists' research.

In the 1980s, former Soviet scientists used the free rib forming method to create a composite material network structure [5]. Although the load-carrying efficiency of the structure is improved compared with the original shell

structure, the fibers are piled up at the grid intersections, making the structural quality of the ribs poor. This is a great exploration of the fiber winding method by researchers (as shown in Figure 5(b)).

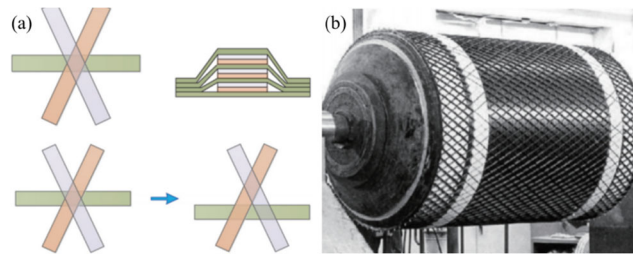


Figure 5. (a) Fibers intersection of three directions and offset the stiffeners at intersection (b) Free winding of helical ribs

Huybrechts et al. found that during the heating and curing process, silicone rubber expands by heat and squeezes the fibers from the side, thereby improving the uneven distribution of fiber resin content, thereby reducing the

defects in the grid structure, by increasing the structure level, the structural quality can be reduced. and its structural properties can be changed[6].

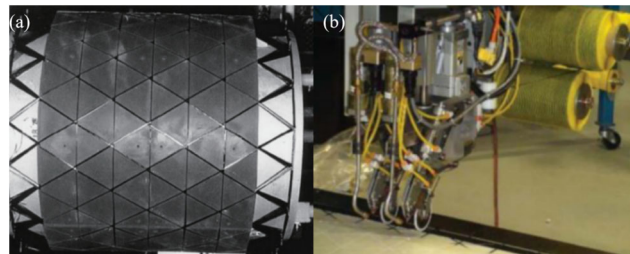


Figure 6. (a)Forming of isogrid stiffened cylinder in rubber tooling (b)Grid structure fabrication head

Li et al. and Wu et al. respectively designed and prepared two multi-level cylindrical grid structures, both of which use a secondary network, which is divided into a primary network structure and a sub-level network structure (as shown in Figure 12) [7, 8]. In terms of design, the reinforcement ribs of the primary network structure are thicker and higher. The primary grid structure is used to improve the overall bending stiffness of the structure, and the sub-level network can improve the local stiffness of the structure. The comparison of the data of the two teams shows that the ultimate load of the grid structure of the equitriangular pattern is about twice that of the orthogonal grid pattern. In addition, there are pin reinforcement molds, metal grid molds and so on(as shown in Figure 7), but silicone rubber molds are still the first choice

for grid winding molds, which have the characteristics of flexible application and good applicability.

In addition, the automatic laying technology can effectively improve the fiber overhead at the intersection point and reduce the porosity. Therefore, automatic laying technology is another focus of scientists' research. According to the different fiber laying process, the intersection point can be divided into three different basic structures (as shown in Figure 8). Mangas et al. and Mack et al. conducted tension and compression tests on these three structures, and found that the first structural bending strength is higher and it has more advantages in terms of mechanical properties and manufacturability [9, 10].

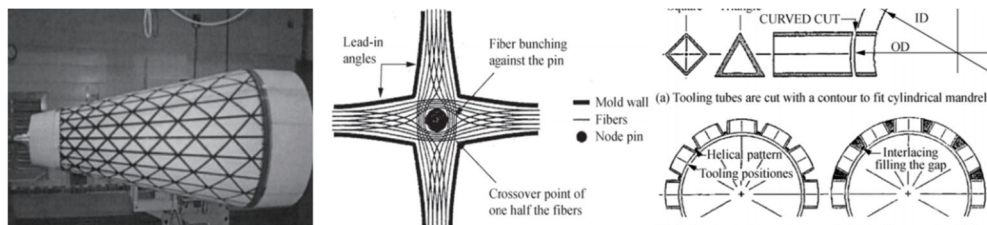


Figure 7. Different mold processes (from left to right: hybrid tooling, pin enhanced geometry process and Tooling reinforced interlaced grid process)

ICCI has designed a special wire laying head with a grid structure (as shown in Figure 6(b)), so that it can penetrate deep into the groove of the grid structure, providing technical support for automatic laying[11].

Müller et al. obtained a rib structure with stable shape and good quality by controlling the pressure during the rib laying process(as shown in Figure 9)[12].

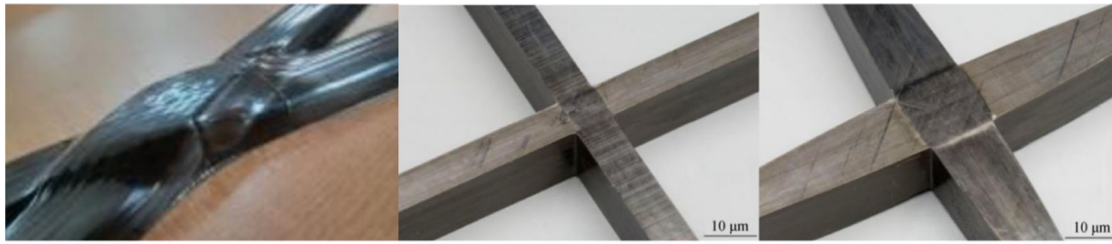


Figure 8. Three different structures at intersections (From left to right: first, second, third)



(a) Unstable rib

(b) Stable rib

Figure 9. Forming of grid rib without tooling

Han et al. and Zheng et al. used the interlocking process to prepare a unique grid structure, which splices the ribs together. This method significantly improves the bending resistance

and energy absorption capacity of the structure under compressive load (as shown in Figure 10 (a)) [13, 14]

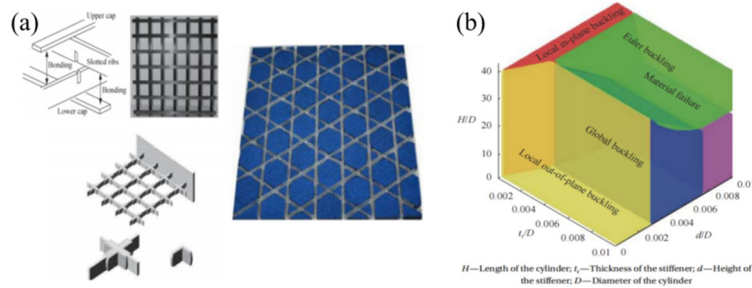


Figure 10. (a) Forming of grid panels by interlocked process
(b) 3D- failure mechanism map of lattice cylinder[16]

3.3. Mechanical Properties

There are generally three failure modes for lattice shell structures under axial compression loads: overall buckling of the shell, local buckling of ribs and failure of rib collapse. In recent years, scientific researchers have gained a clear understanding of the structure through methods such as theoretical model data simulation and experiments.

In terms of theoretical models, Zhang et al. established triangular, Kagome-shaped and hexagonal theoretical models, and verified them with finite elements[15]. The results show that Kagome-shaped and triangular mesh cylindrical shells have approximately equal load-carrying capacity, and both have higher axial compression performance than hexagonal mesh cylindrical shells. Li et al. used the Rayleigh-Ritz method and Totaro theory to deduce, drew a 3D- failure mechanism diagram(as shown in Figure 10(b)), which makes the respective isolated failure models expressed by specific composite functions, providing a theoretical basis for calculating the failure model[16].

In terms of experiments, Zhou et al. and Zheng et al. conducted a systematic study on the preparation process of the composite grid structure and its stiffness and strength analysis methods [17, 18]. The research shows that the Kagome configuration has obvious advantages in terms of stability, and based on the homogenization method, four

failure modes of Kagome configuration under axial load are studied: overall buckling, local out-of-plane buckling, local in-plane buckling and strength failure. At the same time, it is pointed out that the model with a large size is mainly dominated by overall buckling failure. The relationship between stiffness and support width or thickness is linear, while the relationship between critical force and support thickness is a quadratic relationship, which is consistent with the results shown in Figure 10(b).

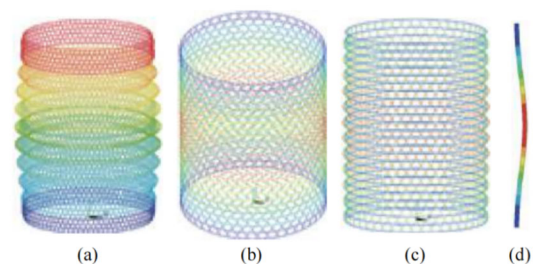


Figure 11. Possible failure modes of grid cylinder[16]
(a) Global buckling;(b) Local in-plane; (c) Local out-of-plane buckling;(d)Euler buckling)

In addition, Lai et al. conducted research on structural design, preparation process and mechanical properties, and

the results showed that: Kagome grid structure has end delamination failure and out-of-plane buckling failure(as shown in Figure 11) [19-21]. Therefore, Li et al. used fiber winding technology and co-curing technology to prepare two types of composite reinforced tubes, flange type and end wrapping type (as shown in Figure 12)[22].



Figure 12. Hierarchical Kagome stiffened cylinder

4. Application of Composite Lightweight Shell Structure

The grid shell structure is widely used in various fields, specifically in the field of aerospace. In rocket applications, there are mainly structures such as rocket stage sections, fairings and other structures (as shown in Figure 13(A)). The Proton-M rocket developed by the Russian Space Agency adopts an interstage structure, which has a good ultimate compression load and a good carrying capacity.

The application in the satellite is mainly the satellite bearing tube. The load-bearing tube is the main load-bearing component of the satellite structure (as shown in Figure 13(B)), and plays an important role in the overall stability of the satellite structure. For example, China’s Fengyun-3 and Asia-Pacific 2 satellites both use this structure.

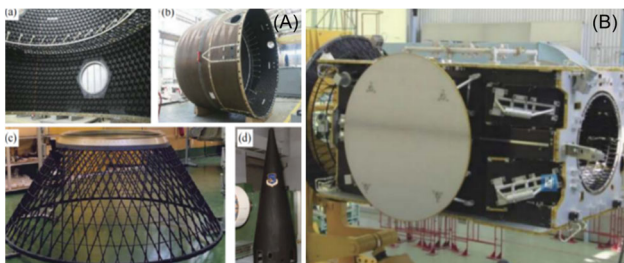


Figure 13. (A) Applications in rockets and missiles (B) Applications in satellite

In addition, the structure is also broadly used in the field of civil airliners. According to data, the European Airbus company Airbus has widely used composite materials with this structure on A300, A330 and other aircraft (as shown in Figure 14)

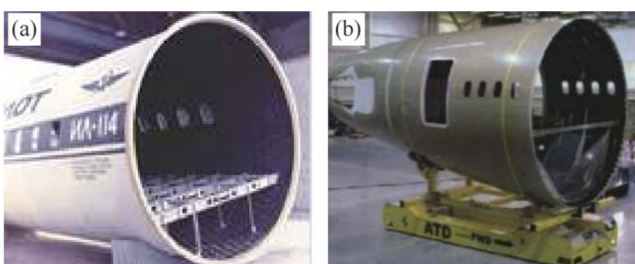


Figure 14. Applications in aircraft

5. Conclusion and Outlook

This paper mainly starts from Kagome, and studies the development and application of lattice shell structure in detail. In recent years, scientific researchers have conducted comprehensive and detailed research on the structure by using theoretical models, numerical simulations and experiments, and found that the lattice shell structure designed on the basis of Kagome has good mechanical properties. However, the preparation process is still immature at this stage, and there are still difficulties in mass production and high production costs, which will certainly become the point of future work.

We predict: the future development direction is as follows:

(1) Exploration of mass production and low-cost processes.

At present, the cost and performance of the grid structure have a lot to do with the forming process. Although the new forming process has superior mechanical properties, its cost will be greatly increased and mass production is difficult. Therefore, how to simplify the production process to reduce the cost is a problem to be solved in the future.

(2) Optimal design and performance improvement of grid shell structure. The grid structure has better load-bearing efficiency than other structures, and the design of the grid is the focus of the structure. How to layout a more efficient grid structure is one of the future development directions.

(3) The connection between the lightweight composite shell structure and other components. Components with a grid shell structure are usually the core components of rockets, so how to properly solve the problem of connection with other components and make them function to the greatest extent is a key issue in the future.

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