Comparison Structure Forms Between Isogrid and Orthogrid of C/E Composite Trellis Wound Structure Based on Calculation of Load-Carrying

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Abstract This paper calculated load-carrying of isogrid and orthogrid of carbon-epoxy composite trellis wound structure (C/E CTWS) using non-linear finite element method. Based on the analysis, test cases were designed and tests of axial compression were carried. Analysis result and test result fit well. In order to be used in the project, this kind of structure cut-out repairing was calculated. The method presented in this paper has been proved and can be used to solve complicated engineering problems. According to calculations and experimental results combined with application, a principle of choosing wound structure is obtained and principle could be applied to engineering.

Key words C/E Composite trellis wound structure (C/E CTWS), Calculation of load-carrying capacity of the structure, Static test

1 Introduction

The carbon-epoxy composite trellis wound structure (C/E CTWS) is widely used in astronautic industry due to its outstanding properties. It is required to study the analysis method of the C/E CTWS.

We could select FEM geometric nonlinear calculation parameters and study the mechanical response to the C/E CTWS under axial compression to obtain the failure load of structure[1-4].

Through comparing experimental results, we could verify the accuracy of the analysis result. The structural efficiency between isogrid and orthogrid of the C/E CTWS was compared on the base of the test results. The application principle of different grid forms will be determined according to actual application of the structure.

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2 Load-carrying calculation under axial compression of isogrid cylindrical shell and experimental confirmation

Because the load of the C/E CTWS cylindrical shell and conical shell is primarily undertaken by the reinforced grid ribs, the skin of the structure is quite thin. The skin of the structure can carry sheer load and maintain the shape of the grid ribs. When bearing a greater load, the structure will cause buckling and post-bucking behavior. The result of the tests and analysis indicate that the efficiency of the C/E CTWS cylindrical shell can be increased by considering the post-bucking response. If the post-buckling behavior of the structure is incorporated into the design method of security state, the skin of the structure could be thinner. Compared with the traditional design by taking critical buckling load as ultimate load, it can obviously reduce the structural weight and raises the structure efficiency. As the calculation of post-buckling analysis is complicated, the consideration of the post-buckling increases the difficulty of the structural design and needs much longer time.

The C/E CTWS will be analyzed by using the finite element analysis software MSC. Nastran. In the finite element model of the C/E CTWS cylindrical shell, 75 units provided by MARC will be used for modeling the skin and the grid ribs. The boundary condition is applied like this, the 6 degrees of freedom of the bottom is constrained. The axial compression is applied on the top

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of the structure. The axial compression is applied by using the technical implementation of multi-point constraint.

The response of the structure under quasi-static compression is solved by using nonlinear finite element method. The structure misalignment behavior is analyzed by using the Newton-Raphson algorithm to obtain the response of the buckling and the post-buckling and the failure load of the structure.

We have designed an isogrid C/E CTWS cylindrical shell, so we could analyze the structure and produce a test case to testify the calculation result.

The isogrid C/E CTWS cylindrical shell includes outer skin and reinforcement grid ribs, which is carbon fiber with epoxy enhancement resin. The skin is laminated shell which is symmetrically layered and the skin thickness is suitably selected. Its height is 666 mm and its diameter is 1 700 mm. The direction of the reinforcement fiber only followed the direction of the grid ribs. The height and the width of the grid ribs and the altitude of the isogrid is appropriately chosen.

In order to compare the fiber performance, we name the carbon fiber No. 1. The material properties are shown in table 1.

Tab. 1 Material properties

E_{11}/GPa	E_{22}/GPa	v_{12}	G_{12}/GPa	ρ/ g·mm^{-3}
181	10.3	0.28	7.17	0.0016

The finite element model was made. The structural finite element model is shown in figure 1. Then the quasi-static analysis under axial compression was carried on.

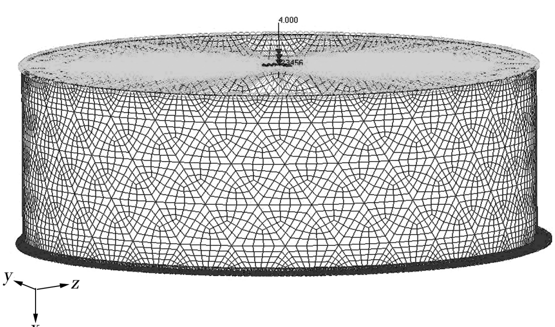


Fig. 1 Finite element model of isogrid C/E CTWS cylindrical shell

Figure 2 shows the typical load-displacement curve of the isogrid C/E CTWS cylindrical shell under the quasi-static axial compression. The horizontal axis represents displacement loading process. Time displacement shows the proportion of the total displacement. The vertical axis represents the structural load. Take a number of points in the curve to illustrate the characteristics of the structure. At the same time, the deformation contours of the structure are given in the corresponding time. It can be seen from the curve that the structural load changes in stage corresponding with the changes of the displacement load. Firstly, in the stage AB, the load changes linearly with displacement, structural deformation is evenly distributed on the whole. Then the critical buckling of the structure occurs at point B. Buckling mode is local skin buckling in the grid ribs; In the stage BC, the structure gets into the post-buckling stage, the relationship between load and displacement is nonlinear, structural rigidity decreases compared with the phase AB, but the structure is still able to load continuously; At the point C, it reaches the peak load. Then the load decreases sharply. Finally, at the point E, the structure shows a large area of skin deformation, together with buckling of the grid ribs and a great loss of carrying capacity occurs. The structure is damaged.

In this figure, point C is corresponding to the peak load, or the critical load. It is regarded as the carrying capacity of the target structure. From the above discussion, it can be seen that the structure of the post-buckling stage can be allowed to occur in the structure of the working process. But so far, the traditional method always regards the critical buckling load as the design load for the similar problem, which does not allow post-buckling to occur. Compared with the critical buckling of the traditional method, the current study uses the post-buckling method. It can further reduce structural weight under the same limited load requirements. The calculation value under the axial compression load is 1 613 kN. It is shown in figure 2.

The weight of the isogrid reinforcement cylindrical shell structural test case under the axial compression is 11.5 kg except for the weight of the frames. The static test demonstrated that structure shows local skin buckling between the grid ribs when the axial compression gets to 700 kN. When the axial compression achieves 1 515.24 kN, the structure is buckling. The finite element analysis result and the test result shows in table 2. By comparing the finite element analysis result and the test result, we can conclude that the analysis result and the test result fit well. This explained the computational method of this article can be used in load-carrying calculation of the C/E CTWS.

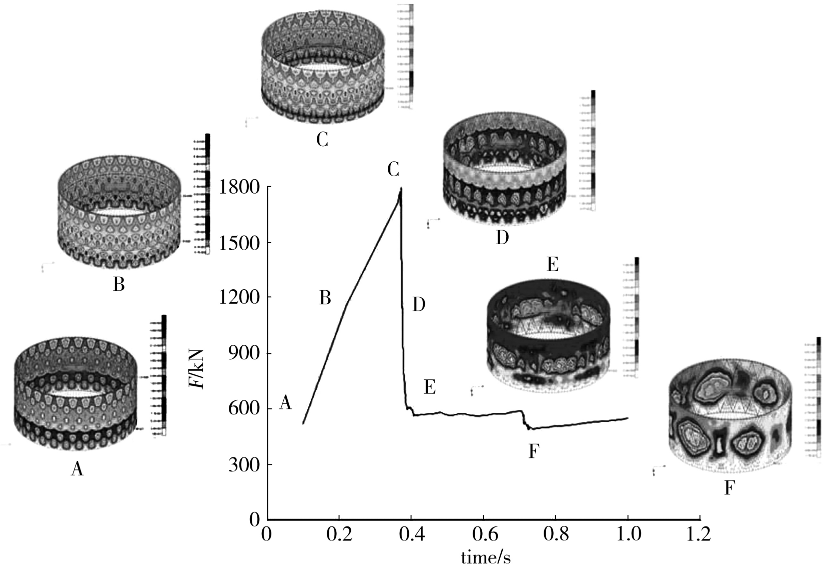


Fig. 2　Typical load-displacement curve of isogrid C/E CTWS cylindrical shell under quasi-static axial compression

Tab. 2　Contrast of analysis results and test results

Items	Skin buckling axial compression/kN	Overall buckling of axial compression/kN
analysis results	738.9	1613
test results	Approximately 700	1515.24
Analytical error	-	6.5%

3　Load-carrying calculation under axial compression of orthogrid conical shell with large cut-out and experimental confirmation

The computational method of the orthogonal grid C/E CTWS is the same as the load-carrying calculation of the isogrid C/E CTWS. When we design rocket structure, conical shell is inevitable. Because there are many appearance to be installed and operated, the cut-out is inevitable. If we hope that the C/E CTWS can be used in the rocket structure, we should design orthogonal grid composite conical shell referring to the practical application of the rocket structure. Considering the influence of the large cut-out, we can analyze and calculate the load-carrying, and produce the same size test case as the finite element model to verify the result.

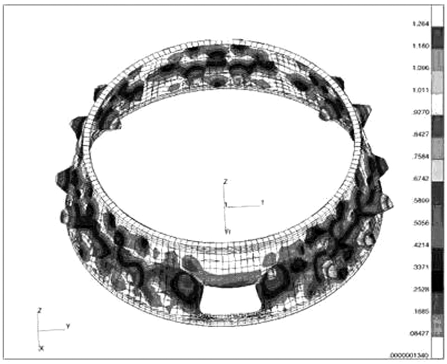
As the isogrid C/E CTWS cylindrical shell, the orthogrid C/E CTWS conical shell also includes outer skin and reinforcement grid ribs, which is carbon fiber with epoxy enhancement resin. The skin is laminated shell which is symmetrically layered and the thickness of the skin is suitably selected. The direction of the reinforcement fiber only follows the direction of the grid ribs. The height and the width of the grid ribs and the distance between the longitudinal grid ribs and vertical grid ribs of the isogrid are appropriately chosen. The difference is that the skin is a conical shell. Its height is 558.5 mm. Its top diameter is 1 480 mm and its semi-conical angle is 10.5°. There is a large cut-out in the III-IV quadrant. Its length is 230 mm along the longitudinal line and its central angle is 25° (the arc length of the cut-out center is about 354 mm). The angle between the longitudinal center line and the Quadrant IV is 35°. The distance between the front edge of the cut-out and the upper frame is 245 mm.

When we calculate the load-carrying of the orthogridC/E CTWS conical shell, we mainly consider the influence of the cut-out without cover.

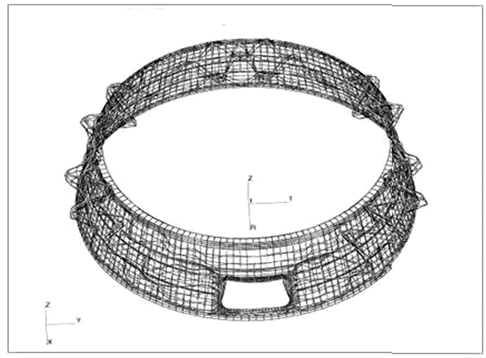
It is discovered through analyses that the place near the cut-out is the most dangerous position which would firstly buckle for the composite conical shell. The structural and the mechanical properties of the material could not be used effectively unless the effective cut-out reinforcement would be adopted.

Because the big cut-out is not covered, the skin stiffness is not continuous. The load-carrying of the big cut-out structure which is repaired could not reach the load-carrying of the structure without cut-out. The analysis result also shows that the structure is less efficient and the reinforcement effect is not obvious by simply increasing the thickness of the skin around the cut-out. Therefore, we design the high flange to strengthen the cut-outs. The altitude of the flange is 35 mm. The width of the flange is 3 mm. The width of the overlap between the frame and the shell is 35 mm and the thickness is 3 mm.

Through computation and comparison between different structural designs we discovered that the longitudinal ribs could effectively share the vertical load. Through increasing the number of the longitudinal ribs, the buckling load is obviously enhanced and the stress concentration is alleviated. But the initial buckling region is not shifted obviously by increasing the number of the longitudinal ribs. By adjusting the structural parameters, the structure could buckle in complete cycle as far as possible. The result is shown in figure 3.



(a) Structure could buckle in complete cycle



(b) Shape of the buckling

Fig. 3 Structure in complete cycle of buckling can increase carrying capacity

The test only applied axial compression. The damaged compression is 1378.9 kN.

In order to obtain the influence of the cut-out and to compare the performance of the two kinds of the fibers, the structural damaged tests of orthogrid C/E CTWS made of another kind of fiber are carried out. At the same time, the structural damaged tests of orthogrid C/E CTWS made of another kind of fiber and have no cut-out are carried out. The results are shown in table 3.

Tab. 3 Contrast of orthogrid C/E CTWS test results

No.	Material	Failure compression /kN	Condition of tests
1	Fiber 1	1378.9	With cut-out
2	Fiber 2	1320	With cut-out
3	Fiber 2	1410	Without cut-out

The results showed that the carrying capacity of the reinforced large cut-out structure could not reach the carrying capacity of the structure without cut-out, because the skin stiffness is not continuous due to the fact that large cut-out is not covered. The performance of fiber 1 is better than that of fiber 2.

4 Experimental confirmation and grid forms choice

The size (the height and the diameter of the structure) of the isogrid C/E CTWS cylindrical shell and the orthogrid C/E CTWS conical shell which we talked about is quite similar. The conical shell is slightly smaller. Through simple calculation, we could change the orthogrid C/E CTWS conical shell into cylindrical shell which have the same size with the isogrid C/E CTWS and retain its grid characteristic.

Compared with the cylindrical shell, the decline of the conical shell load-carrying is relative to the cosine of the half-conical angle.

$$T_{\text{cone}} = T_{\text{equivalentcloumn}} \cos^2\theta \qquad (1)$$

The diameter of the isogrid is 1 700 mm. When we change the orthogrid conical shell into cylindrical shell, its equivalent diameter is 1 583.5 mm. It can be seen from equation (2) that the equivalent thicknesses of the two test pieces are almost the same. The coefficient k of the dimensionless critical axial compression is decided by the diameter.

$$k = \frac{N_{\min} R}{\bar{E} t^2} \qquad (2)$$

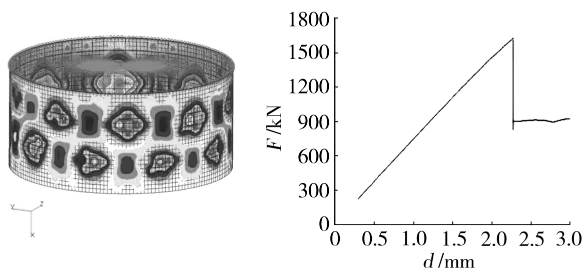
It is difficult to raise load-carrying of the structure with a cut-out which is not covered to load-carrying of structure without cut-out by the method of cut-out reinforcement. This effect can be amended by test results shown in table 3.

We transform orthogrid C/E CTWS conical shell to equivalent diameter cylindrical shell. They have the same size (the height and the diameter of the structure) with Isogrid C/E CTWS cylindrical shell without cut-out. Load-carrying is.

$$\frac{1379}{\cos^2 10.5^\circ} \times \frac{1700}{1583.5} \times \frac{1410}{1320} = 1635 \text{ kN}$$

The weight of the orthogrid C/E CTWS cylindrical shell (without cut-out) which have the same size with isogrid C/E CTWS is 10.8 kg.

Considering the huge cost of the production and the test of theC/E CTWS, it is difficult to produce the orthogrid C/E CTWS cylindrical shell which has no cut-out and has the same height and diameter with the isogrid C/E CTWS to carry on the contrast of the tests. It is impossible to produce and test every grid form that we could think of. Therefore, we calculate the load-carrying of the orthogrid C/E CTWS cylindrical shell which has no cut-out and has the same mesh parameter with the orthogrid conical shell we talked above. The diameter of the structure is 1 700 mm and the height is 666 mm. The results are shown in figure 4. The structure calculation of axial compression is 1 730 kN. Calculation value is 5. 8% higher than the projections. This gap is approximately equal to the analysis error of 6. 5% shown in table 3. Therefore, if we testify the test case, the structure might be destroyed in the projections about 1 635 kN.



(a) Deformed contours (b) Load-displacement curve

Fig. 4 Analysis results of orthogrid cylindrical shell

Tests showed that the phenomenon of local skin buckling is obvious. It exists in engineering applications. So the introduction of geometric nonlinearity in the calculation is reasonable.

According to the functional applications and technological characteristics of the structure, the isogrid and the orthogrid C/E CTWS can be compared as follows:

Isogrid structure is a good structure. The ring grid ribs and oblique grid ribs (spiral grid ribs) form a triangular frame which is a very stable structure. The isogrid structure which is rationally designed has self-stability. Under the axial compression, the oblique grid ribs (spiral grid ribs) change compression into stretch effect of ring grid ribs and skin. The stretch effect is much similar to internal pressure. The ring structure is stabilized by this "internal pressure". It can reduce the sensitivity of the shell to the defects and increase the critical load.

Orthogonal grid is set on the longitudinal reinforcement of the shell. The fiber which forms the grid ribs would get around the shaft of the mold when it is winded. So materials will be wasted and it is difficult to shape the longitudinal grid ribs. It is easy to wind the ring grid ribs and spiral grid ribs on the mold. So isogrid structure has good production efficiency.

But the location of the ring grid ribs and spiral grid ribs can not be adjusted as soon as the triangular height of the isogrid structure is determined. The ribs would be cut off as there is a cut-out. The size of the grids is not equal and the shape of the grids is irregular in the place of the overlap between the cut-out and the grid ribs, so it is difficult to be reinforced. The ring grid ribs and oblique grid ribs (spiral grid ribs) cross together. The space within the grid is inconvenient to install the vertical cut-out reinforcement parts which could raise the load-carrying effectively and equipment support.

For structures which have no cut-out or small cut-out, isogrid C/E CTWS is a good choice. Isogrid C/E CTWS 3D model is shown in figure 5.

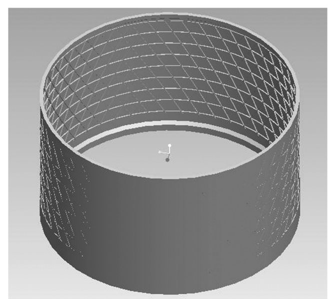


Fig. 5 3D model of isogrid C/E CTWS

There are large cut-outs on some structure's skin. It is extremely unfavorable to transfer the axial compression. So it is needed to increase vertical reinforcement parts to transmit the axial compression. Many apparatus may be installed on the skin of the structure. For this kind of structure, the use of orthogonal grid structure is more realistic.

Composite grid structure studied in this paper has the skin which could maintain the shape of the structure. The ring rigidity is mainly provided by the skin. Even after the continuous skin has locally buckled, the effectiveness of maintaining shape is still much better than the ring grid ribs. Therefore, the numbers of ring stiffeners can be reduced obviously if the local buckling of the skin is allowed in the orthogonal grid structure. While the ring grid ribs of the large diameter composite grid structure is quite heavy, it is important to reduce the weight by reducing the ring grid ribs.

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