Study on Bistable Behaviors of Anti-symmetric Laminated Cylindrical Shell with Different Ply Angles

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Abstract

The anti-symmetric laminated cylindrical shell is a kind of advanced composite structure, which is made by anti-symmetrically arranged continuous fiber in multiple layers held together by a binder. It is proved that anti-symmetric laminated cylindrical shell exhibits unique bistable characteristic. Based on the previous work and the two-point loading experiment, taking T700/TDE-85 anti-symmetric laminated cylindrical shell as an example, this work uses ABAQUS to construct the model of the anti-symmetric laminated cylindrical shell then import it into ABAQUS for modeling the bistable transition process. In this thesis, by varying the geometric parameters of the anti-symmetric laminated cylindrical shell, the effects of the ply angle on the bistable behaviors of laminated structure are systematically investigated. The results show that, with the increase of the ply angle, the induced residual stress and coiled-up radius of the second state increase gradually, however, the steady-state transition critical load remains basically unchanged.

Keywords

Anti-symmetric Laminated Cylindrical Shells, Bistable, Ply Angle, Load-displacement Relationship, Finite Element Method.

1. Introduction

Some composite structures have two different stable state characteristics under certain conditions, which are called bistability. The first research on bistable shell structure is the University of Cambridge, England. Daton-Lovett [1] invented the bistable composite shell in 1996. It is a new type of deployable structure, which can keep stable state during stretching and winding, that is, it has two stable states. As a new deformable structure, the bistable composite structure can be converted in two stable states under the driving of external force, and can maintain a stable state without external force. As a new composite structure, it has a bistable property and can be expanded or rolled up, which makes it have excellent mechanical properties and higher space utilization. Advanced composite structures, such as bistable structures, unfolded composite structures and lattice structures, are widely used in aerospace, energy exploitation and other comprehensive fields. The bistable structure has attracted the attention of researchers from all over the world.

Anti-symmetrical laminated cylindrical shells can be kept stable in both states. As shown in Fig. 1-1, the left side is the first stable state of the cylindrical shell, then the strain energy of the cylindrical shell has a minimum value in this state. The right side is the second stable state of the cylindrical shell, in which the strain energy of the cylindrical shell also has a minimum value. There are two strain energy minimum values for the bistable structure of symmetric laminated cylindrical shell during its deformation process.

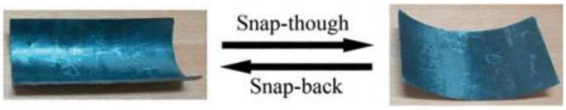

Fig1-1 Two stable states of bistable laminated cylindrical shell

Domestic and foreign scholars have carried out related research on the bistable characteristics of anti-symmetric laminated cylindrical shell structures. The Pellegrino[2]team pioneered a linear elastic model that did not consider the coupling effects of tensile and bending, and successfully predicted the crimp radius of the bistable composite structure. After that, Galletly and Guest[3] simplified the laminated cylindrical shell into a beam model, considering the effect of torsion on the bistable state of the laminated cylindrical shell, and developed a study by the University of Cambridge, England, which successfully distinguished the positive symmetric lamination. Then, based on the "beam model", the second steady radius of the anti-symmetric laminated cylindrical shell is predicted. [4] In recent years, the College of Engineering of Cambridge University has carried out a study on the bistable characteristics of a multi-stabilized composite shell structure containing prestressed isotropic laminated shells and surface folds. Lei Yiming of Tsinghua University studied the mechanical mechanism of the bistable structure during folding and unfolding, and gave the governing equation of the bistable structure. Based on the analysis of the strain energy of the shell structure, a simple relationship between the two steady states of the anti-symmetric laminated cylindrical shell is obtained. By solving the governing equations, it is found that the anti-symmetric laminated cylindrical shell structure is premised that the initial center angle must be greater than a certain critical value[5]. Nie Guohua and Gu Xin of Tongji University studied the mechanical properties of the anti-symmetric laminated cylindrical shell structure and established a bistable structural mechanical model considering the coupling effect of tension and bending.At the same time, the strain energy expression of the anti-symmetric laminated cylindrical shell between two steady states is obtained. [6,7]

In general, asymmetric laminated composite structures have bistable characteristics, and only laminates with laminated angle exhibit cylindrical bistable. Most of the previous work has focused on laminated laminates, but this has been extensively studied for nearly 30 years. However, cylindrical composite structures have bistable characteristics but not necessarily asymmetric stacks. [8, 9] In 1996, Daton-Lovett[1] found that the anti-symmetric cylindrical shell also has two stable cylindrical states. Of course, the anti-symmetric cylindrical shell is made of cylindrical steel dies preloaded on the upper part. This is in contrast to asymmetric laminate laminates which are cured without any support in a press or autoclave and then cooled to room temperature. This means that the initial dimensions and curvature of the anti-symmetric bistable structure can be designed freely according to the actual needs of the project. Therefore, it provides greater design flexibility and wider application to the anti-symmetric cylindrical shell.

2. Basic parameters and modeling

2.1 Basic parameters

The bistable composite structure studied in this paper is an anti-symmetric composite shell composed of a unidirectional T700 carbon fiber fabricated from TDE-85 epoxy. This is a well-expandable expandable space structure. It has the mechanical behavior of small strain and large deformation. The unidirectional T700 carbon fiber has high strength, high elongation, good mechanical properties, and its superior performance is bistable through the anti-symmetric lamination of the cylindrical shell structure[10].

In this paper, a 0.185mm thick unidirectional T700 carbon fiber anti-symmetric composite shell was fabricated from TDE-85 epoxy. Unlike the asymmetric cross-layer laminates, these sized anti-symmetric composite shells are sequentially solidified and cooled in a cylindrical steel mold. Each layer is linearly elastic, and the material properties of the carbon fiber unidirectional plate are shown in Table 2-1. T700 carbon fiber material parameters[11]:

Table 2-1 Material properties of carbon fiber unidirectional plates

$E_{11}(GPa)$	$E_{22}(GPa)$	$G_{12}(GPa)$	$G_{13}(GPa)$	$G_{23}(GPa)$	v_{12}	$t_{ply}(mm)$
132	10.3	6.5	6.5	3.91	0.25	0.185

The geometric parameters of the anti-symmetric composite shell are expressed as follows: longitudinal length $L = 100mm$, initial transverse radius of the neutral layer $R_1 = 25mm$, cross-ply $\beta = 170°$, number of layers $n = 5$(when n is 0, the layup angle of the middle layer is 0) and the ply angle $\alpha = [45° / -45° / 0 / 45° / -45°]$. We can simply write it as: L-R-β-nantiα_shell. For example: 100-25-170-5anti45_shell.

2.2 Establishing a finite element model

The finite element method is used to simulate the steady-state transition process of the anti-symmetric laminated shell, which involves contact and large geometric nonlinear deformation. Especially in the process of deformation from the initial state to the extended state and then a second different steady state. The shell produces large deformation, resulting in large changes in structural stiffness. The commercial finite element software ABAQUS has a strong ability to compute nonlinear problems and is helpful to obtain convergent finite element results. Therefore, this paper uses ABAQUS to calculate the bistable transition process of the anti-symmetric laminated shell.

In order to obtain accurate results and significantly reduce the calculation cost, a four-node reduced integral shell element S4R is used for shell lamination element, and a rigid cylinder with a radius of 5 mm is used to replace the indenter for shell deformation, which is set as an analytical rigid body in the ABAQUS environment. The fixture of composite shell is simplified as two supporting plates, which are arranged as discrete rigid bodies in ABAQUS. The element type is four-node rigid element R3D4, and the distance between two plates is set to 50mm. The material properties of single-layer plates are set in Property, and the laying mode of laminated shells is set according to different conditions. The complete finite element model is shown in the following figure.

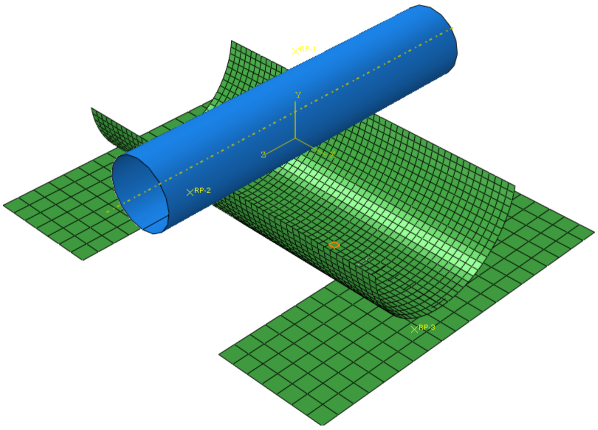

Fig 2-2 Finite element model

3. Results analysis

3.1 Bistable transformation process

Based on ABAQUS and two-point loading method, a 5mm radius indenter model is established. The contact surface of the support is constrained and the boundary conditions of the load and displacement are applied to the rigid cylinder. It is obtained that the anti-symmetric laminated cylindrical shell gradually changes from the first steady state to the second steady state, and then it remains in the second steady state after unloading. As shown in Figure 3-1.

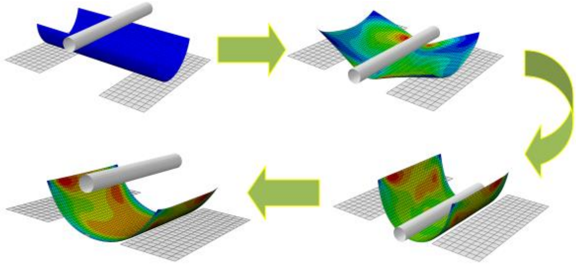

Fig 3-1 Steady-State transition process

3.2 Stress changes during steady-state transition

In ABAQUS, the bistable transition process is viewed step by step. By observing the stress nephogram, it is easy to find that the residual stress is produced by the coupling effect during the transition from the first steady state to the second steady state, as shown in Figure 3-2.

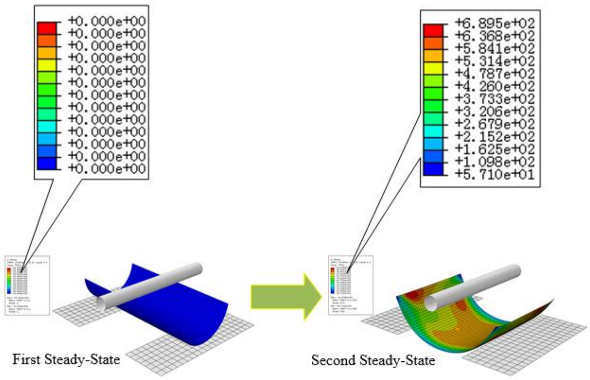

Fig3-2 Residual stresses generated

3.3 Effect of ply angle on bistable characteristics

In order to investigate the effect of laminated shells on the process of bistable transition, the load-displacement curves of different ply angles are given in figure 3-3.

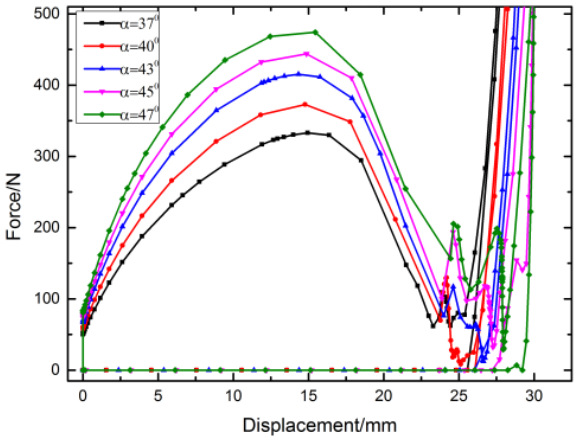

Fig3-3 Load-Displacement curves of 100-25-170-5antiα_shell

It is obtained from Fig. 3-3 that the load of the anti-symmetric laminated cylindrical shell increases with the increase of the radial displacement during the initial loading phase, and begins to decrease after reaching the steady-state transition critical load (load maximum). And then begins to reduce to a certain minimum, the displacement of different layers when the critical load is reached is not very large. Continued loading finds that the load rapidly increases to a peak after a small displacement change. In the unloading phase, the initial unloading phase is similar to the post-loading, with little change in displacement, but the load is rapidly reduced from peak to zero, indicating that the model has reached the second steady state. As the displacement decreases after the unloading, the load remains zero and does not change.

The load-displacement curves of a rigid cylindrical indenter are obtained by numerical simulation of the above five models, as shown in Figure 3-3. According to the principle of force interaction, by comparing the load-displacement curves of five models, it is found that the critical load of steady-state transition increases gradually with the increase of the ply angle from 37° to 47°, and the displacement produced by the critical load of steady-state transition almost remains unchanged.

Fig.3-4 shows Von-Mises stress nephogram on the second steady-state neutral surface of the model. It is found that there is no Von-Mises stress in the first steady-state model, and residual stress is generated in the second steady-state. It should be noted that the maximum Von-Mises stress on the neutral plane increases significantly with the increase of the ply angle.

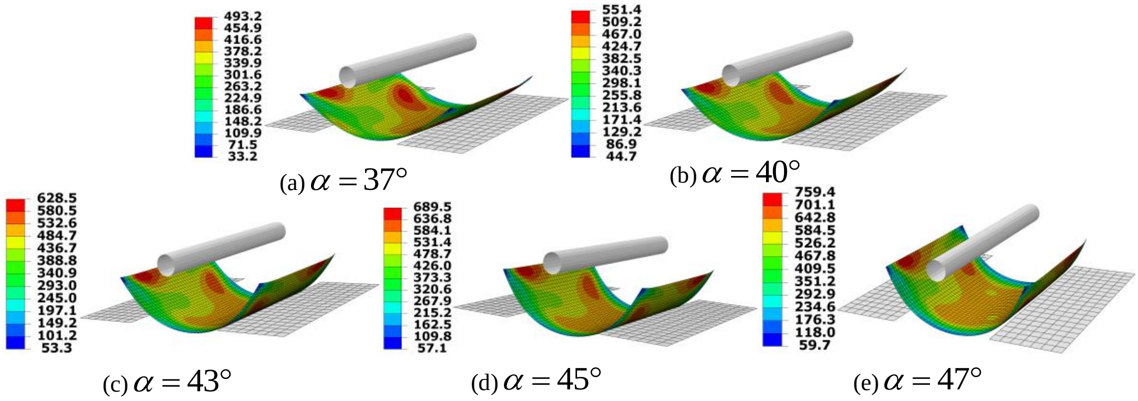

Fig3-4 Second steady-state Von-Mises stress nephogram with different ply angles

Fig. 3-5 shows the effect of different ply angles on the second steady-state curling radius of cylindrical shells. From the figures, it can be seen that the second steady-state curling radius of the above five models are 27.358mm, 28.232 mm, 29.3615mm, 30.0312mm and 30.6521mm, respectively. It is found that the change of the second steady-state curling radius is proportional to the change of ply angles. The larger the ply angles of the anti-symmetric laminated cylindrical shell, the larger the second steady-state curl radius.

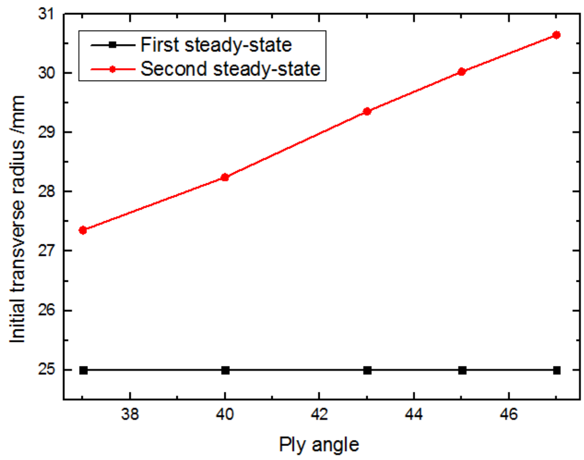

Fig3-5 The steady-state curling radius under different ply angles

4. Conclusion

In the initial loading phase, the load of the anti-symmetric laminated cylindrical shell starts to decrease to a certain minimum after the steady-state transition of the critical load, and the load continues to be found, after a small displacement change, the load increases rapidly to a peak. During the unloading phase, the initial unloading phase is similar to the post-load and the displacement varies very little, but the load is rapidly reduced from peak to zero, indicating that the model has reached the second steady state. As the displacement decreases, the load remains constant at zero, which indicates that the rigid cylinder head has been separated from the shell in this stage. By observing the stress nephogram in the process of bistable transformation, it is found that the residual stress occurs during the transition from the first steady-state to the second steady-state, that is, plastic deformation occurs in the shell.

When the other geometric parameters of anti-symmetrical laminated cylindrical shells remain unchanged, the critical load of steady-state transition increases gradually with the increase of the ply angle from $37°$ to $47°$, and the displacement produced when the critical load reaches the steady-state transition almost remains unchanged, but the change of the second steady-state crimp radius is proportional to the change of the ply angles. The larger the lay angles of laminated cylindrical shells are, the larger the second steady-state curling radius are. It is indicated that the ply angle has great influence on the second steady-state curling radius of the anti-symmetric laminated cylindrical shell.

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