Optimization of Composite Cylindrical Shell Subjected to Hydrostatic Pressure

Guang Pan, Jiangfeng Lu(✉), Kechun Shen, and Jiujiu Ke

School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, People's Republic of China
winf.23@gmail.com

Abstract. Composite is used to substitute aluminum alloy as material of the underwater vehicle in this study. Nonlinear buckling behaviors of composite cylindrical underwater shell are studied using ANSYS software. Carbon/Epoxy is selected as material of the vehicle through comparative analysis. Optimization of ply sequence, thickness and angle of composite cylindrical shell subjected to hydrostatic pressure is investigated. Both buckling and material damage is considered in the optimization, the results show that buckling is the major destroy form. The vehicle's buckling pressure is greatly increased after optimization. And the vehicle's working depth has a 32% increase without changing its shape and structure.

Keywords: Underwater vehicle · Composite material · Finite element · Optimization

1 Introduction

Cylindrical shell has high pressure resistance and good hydrodynamic characteristics, so most automatic underwater vehicles (AUV) are cylindrical. And composite material has high strength: weight ratio, good corrosion resistance, good sound absorption performance, good manufacturability, long service life etc.[1]. These good properties make composite a suitable material for underwater pressure vessels.

R.K.H.Ng [2] studies E-glass/Epoxy shallow water composite pressure vessel, finds that its strain and stress safety factor are 17.17 and 11.95, but buckling safety factor is only 1.25. That means buckling damage occurs before stress damage, which is the main failure mode. Therefore, it is very meaningful to study the buckling behavior of composite cylindrical shell subjected to external hydrostatic pressure.

Gyeong-Chan Lee [3] uses a micro-genetic algorithm to optimize underwater composite sandwich cylinders, the result shows that both buckling and material failure should be considered.

Tanguy Messager [4] uses a genetic algorithm to optimize ply angle and sequence of thin underwater composite sandwich cylindrical vessels, the result shows that specific $\left[90_{N1}\psi_1\phi_{N2}\psi_2 90_{N3}\right]$ patterns can induce significant increase of buckling pressure.

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The author has studied buckling behaviors of underwater composite cylindrical hull by nonlinear method, finds that buckling pressure changes through varying ply thickness, angle and sequence. In other words, the buckling pressure of underwater cylindrical shell can maximize through optimization of ply thickness, angle and sequence.

Nonlinear buckling numerical analysis method is adopted to study the buckling behaviors of AUV shell, which greatly improves the accuracy. By contrast, proper material Carbon/Epoxy is selected as AUV shell's material. And the method of distribution optimization is used to design composite layers to achieve maximum of AUV detection depth.

2 Description of the Problem

An aluminum automatic underwater vehicle (AUV) named V8 has been made for underwater detection several years ago, the max detection depth is 10 m. Due to working requires, the vehicle's working scope needs to be elevated to 16 m. V8's detection depth is increased by substituting aluminum to composite material in this study, maintaining its shape and wall thickness the same. Then, the AUV's working scope will be increased without redesigning, saving a lot of time and money.

The AUV's cross-sectional view is showed in Fig. 1. And its dimensions are as follows: a length of 1850 mm, an outer diameter of 200 mm, a wall thickness of 3 mm, a rib number of 7, a rib space of 211 mm, a rib thickness of 3 mm, and a rib width of 5 mm.

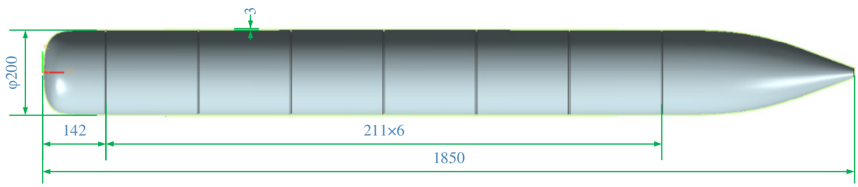

Fig. 1. The cross-sectional view of the vehicle

3 Finite Element Analysis Verification

Seong-Hwa Hur [5] uses a nonlinear finite element software, ACOSwin, to study the postbuckling behavior of composite cylindrical underwater shell. The deviation between simulation and experiment is about 15%.

The concept of defects factor (*DF*) is introduced when considering model's geometric imperfections [6], and finite element software, ANSYS, is used to study nonlinear buckling behaviors of composite cylindrical shell subjected to hydrostatic pressure in this paper. The deviation between simulation and experiment is about 5%.

In order to apply the proper geometry imperfections, *DF* needs to be estimated reliably. *DF* is equal to the ratio of manufacturing errors (*MT*) with maximum displacement (*MD*) of first-order linear eigenvalue buckling, as shown in Equation 1.

$$DF = \frac{MT}{MD} = \frac{0.17}{1.035} = 0.164 \tag{1}$$

The finite element model and boundary conditions are showed in Fig. 2. The model's dimension is 316 mm (diameter) ×600 mm (length). Left end of the model is unclosed, and right end is closed by 13 mm thick carbon steel. Left end is applied fixed constraint, right end is only allowed axial displacement, circumferential direction and right end are exert uniform pressure load.

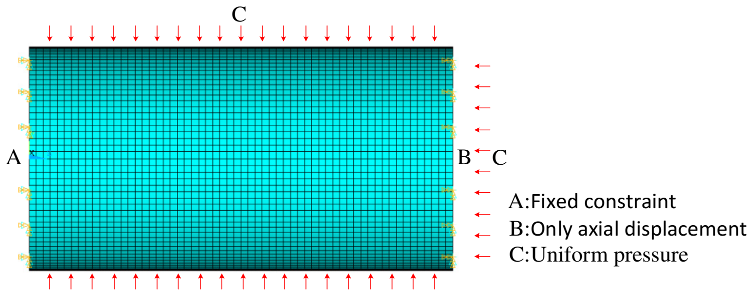

Fig. 2. The finite element model and boundary conditions

The displacement of node 1078 is max of the model. And pressure vs. displacement curve of node 1078 is showed in Fig. 3. As can be seen from the figure, the curve reaches the peak at 0.57MPa, then change of pressure causes a sharp change of displacement, which shows that buckling behavior of cylindrical shell has occurred. Experimental buckling pressure [5] is 0.55MPa, and finite element buckling pressure in this paper is 0.57MPa, relative error is 5%, agreed well with the experimental results.

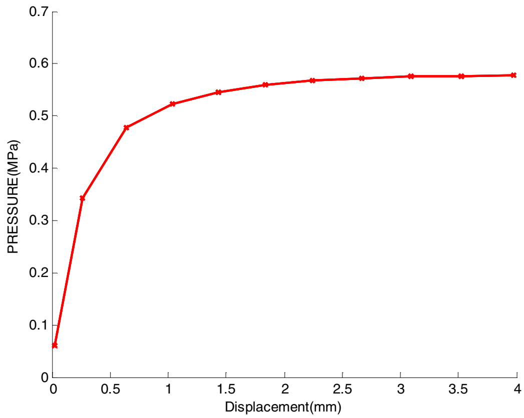

Fig. 3. Pressure vs. displacement curve of node 1078

4 Material Selection

The selected material must be able to withstand the harsh marine environment, because the optimization purpose is realization of the AUV's bigger detection depth. Under the deep-sea environment, requires of material are as follows [7]:

- High resistance to water pressure;
- Good corrosion resistance;
- Good sound absorption performance;
- High strength: weight ratio;
- Long service life;
- Acceptable price.

Resin-based composite materials Carbon/Epoxy, Boron/Epoxy, Glass/Epoxy can meet the above requirements. The three materials' matrixes are all Epoxy, but fibers are different. Comparisons of fiber properties are showed in Table 1 [8]. Differences of fiber properties lead to different composites' properties, elastic properties of the three composite materials are showed in Table 2 [9-11].

Table 1. Comparisons of fiber properties

Fiber	Tensile Modulus ,*GPa*	Tensile Strength ,*GPa*	Density ,g/cm^3	Price ,*$/kg*
Carbon	207-345	2.41-6.89	1.75-1.9	44-220
Boron	400	5.03-6.89	2.3-2.6	220-550
Glass	69-86	3.03-4.61	2.48-2.6	11-88

Table 2. Elastic properties of composite materials

Material	Carbon/Epoxy	Boron/Epoxy	Glass/Epoxy
E_{11}/GPa	162	206.8	45.6
E_{22}/GPa	9.6	18.62	16.2
E_{33}/GPa	9.6	18.62	16.2
G_{12}/GPa	6.1	4.482	5.83
G_{23}/GPa	3.5	2.551	5.78
G_{13}/GPa	6.1	4.482	5.83
υ_{12}	0.298	0.21	0.278
υ_{23}	0.47	0.45	0.4
υ_{13}	0.298	0.21	0.278
$\rho/g/cm^3$	1.32	2.11	1.85

In order to choose a more suitable material for AUV shell, a comparative analysis of the three composite materials is done. As shown in Fig. 4, buckling pressure vs. ply thickness curves of different materials shell are studied at specific $[90_5/60/60_6]_s$ stacking sequence.

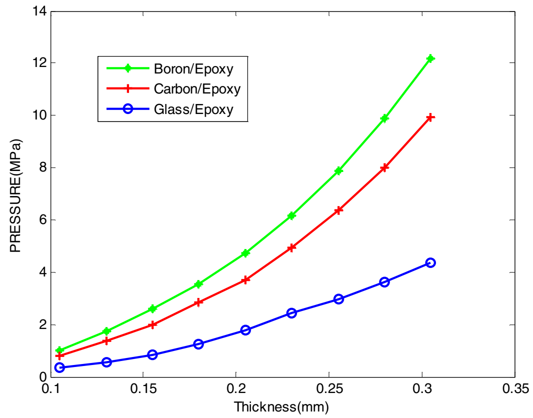

Fig. 4. Buckling pressure vs. ply thickness curves of different materials shell

As can be seen from Fig. 4, the buckling pressure of Boron/Epoxy shell is the largest, but the price is the highest, and the density (2.11g/cm3) is the largest, so the material is only applicable to improve the buckling pressure; the buckling pressure of Glass/Epoxy shell is the smallest, but the price is the lowest, and the density (1.85g/cm3) is smaller, the material is only applicable to pursue cost; the buckling pressure of Carbon/Epoxy shell is the larger, and the price is lager, but the density (1.32g/cm3) is the smallest, the material is applicable to pursue comprehensive performance. Based on the above analysis, Carbon/Epoxy is chosen as AUV shell's material in this study.

5 Optimization

The method of distribution optimization is used to design composite layers in this paper. Firstly, ply angle and thickness are optimized, the numbers of layers can be got through total thickness divided by single thickness. Then according to the number of layers, ply sequence is optimized by Genetic algorithm (GA) [12-14].

Taking into account the case of the same design parameters, such as rib geometric parameter, rib arrangement, shell thickness, destroy is most likely to occur in the middle of the AUV shell [15]. Thus only buckling behavior of the shell's middle section is studied.

Optimization of Ply Angle and Thickness

$[0/\pm\phi/90]_s$ and $[0/\pm\theta/90]_s$ are set as stacking sequence of casing and ribs respectively. In order to facilitate the expression of ply thickness, some rules are set as follows: t_{ij} represents ply thickness, $i=1,2$ represent casing and rib respectively, $j=1,2,3,4$ represent 0°, ϕ° & θ°, $-\phi^\circ$ & $-\theta^\circ$, 90° respectively. Optimization variables include ply angles ϕ, θ and ply thickness t_{ij}.

Mathematical model of optimization is shown below:

$$\begin{aligned} &\max\ pre. \\ &0 \le t_{ij} \le 1.5 \\ &\sum_{j=1}^{4} t_{1j} = 1.5, \sum_{j=1}^{4} t_{2j} = 1.5 \end{aligned} \quad (2)$$

The objective function of optimization is to maximize the buckling pressure, constraints are to maintain the model geometry constant, and make Tsai-Wu coefficient less than 1. The initial value of variables are set as follows: $\varphi=\theta=45°$, $t_{ij}=0.375$ mm.

ANSYS is integrated into ISIGHT to complete optimization of ply angle and thickness in this study. Variables and constraints are set in ISIGHT, finite model is established and result is solved in ANSYS, then the desired result is returned to ISIGHT to determine convergence or not.

Optimization result of ply angle and thickness is shown in Table 3. Due to restrictions on the laying process, ply angle is rounded to 45°. Single-layer material thickness of Carbon/Epoxy is 0.1 mm, and ply layers are integer's layer [16]. Thus the thickness of each layer value needs to be rounded after optimization, the rounded value is an integer multiple of 0.1. Round result is also shown in Table 3.

Table 3. Optimization result of ply angle and thickness

variable	ϕ	θ	t_{11}	t_{12}	t_{13}	t_{14}	t_{21}	t_{22}	t_{23}	t_{24}
Opti.	46	45	0.862	0.095	0.094	0.447	1.032	0.092	0.092	0.283
Round	45	45	0.9	0.1	0.1	0.4	1.0	0.1	0.1	0.3

Buckling pressure comparison chart between before and after optimization is shown in Fig. 5. The initial buckling pressure is 1.4456 MPa, buckling pressure becomes 1.6512 MPa which is 14.22% larger than the former after optimization.

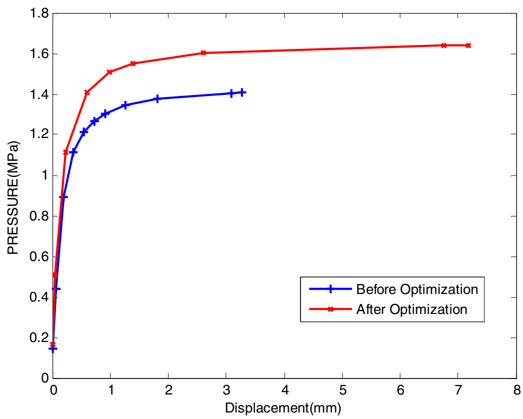

Fig. 5. Buckling pressure comparison chart between before and after optimization

Tsai-Wu criterion is used in this paper, because the theory and experiments are well consistent with each other [17-19]. Tsai-Wu failure factor graph of the vehicle is showed in Fig. 6. As shown in Fig. 6, the maximum Tsai-Wu failure factor is 0.92, less than 1, thus the vehicle's material is safe.

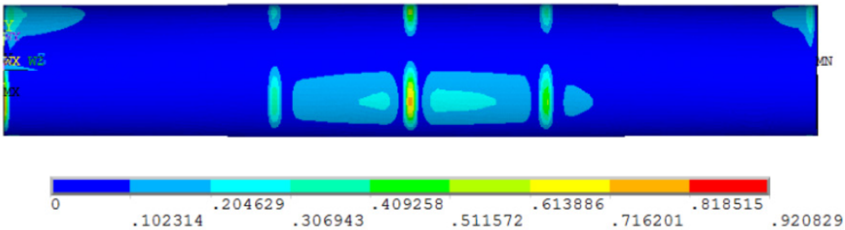

Fig. 6. Tsai-Wu failure factor graph of the vehicle

After optimization, stacking sequence of casing is $[0_9/\pm45/90_4]_s$, and stacking sequence of ribs is $[0_{10}/\pm45/90_3]_s$.

Optimization of Ply Sequence

Variables of stacking sequence are all discrete variables, and GA's integer encoding strategy is good at optimization of discrete variables, thus GA is selected as optimization algorithm.

The principle of GA can be described by biological evolution: parameters of problems need to be solved are encoded to form a gene by binary coded or decimal code; then a chromosome is consisted by several genes; initial population is consisted by several chromosomes; new chromosomes and population are consisted after selection, crossover, mutation; optimization is over after several times iteration until optimal chromosomes are got.

After ply angle optimization, $0^\circ, 45^\circ, -45^\circ, 90^\circ$ are chosen as laying angle, they are all discrete. According to integer encoding strategy, inters 1,2,3,4 represent $0^\circ, 45^\circ, -45^\circ, 90^\circ$ respectively. Thus $[1_9/2/3/4_4]_s$ represents stacking sequence of casing, and $[1_{10}/2/3/4_3]_s$ represents stacking sequence of ribs.

As layers of the vehicle are symmetrical, shell needs to define the stacking sequence of 15 layers, and ribs need to define the stacking sequence of 15 layers too. A total of 30 layers need to be defined, therefore gene number of chromosome is 30. The chromosome is called parent chromosome, and it's expressed as: $[1_{10}234_3/1_9234_4]$.

Flow chart of ply sequence optimization is shown in Fig. 7. To expand on the procedure flowchart, each step is explained here.

Step 1: The chromosome is decoded into ply angle using Matlab.
Step 2: ANSYS is called to complete modeling and solving by Matlab.
Step 3: The result is returned to Matlab to calculate the fitness value by ANSYS.
Step 4: Selection, crossover and mutation is conducted in Matlab.
Step 5: The above iteration is conducted until convergence.

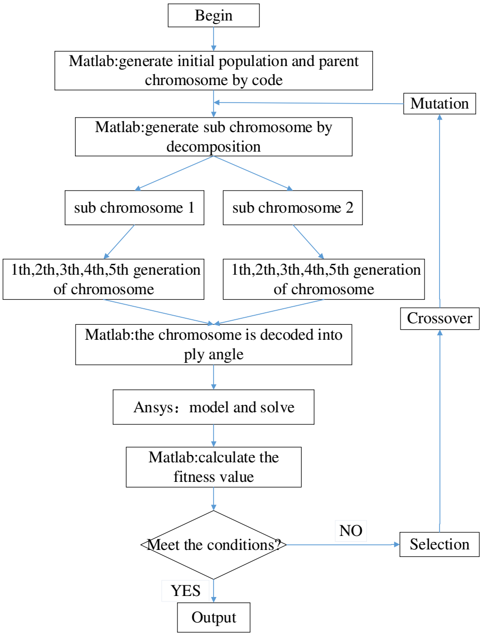

Fig. 7. Flow chart of ply sequence optimization

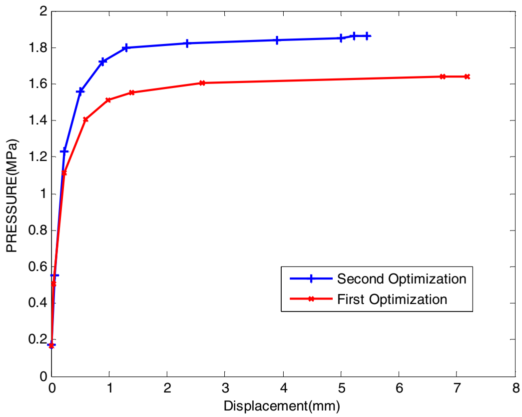

Fig. 8. Comparison chart of two times of optimization results

After 106 iteration, the result has been convergence. The ply sequence of casting and ribs are [±45/0/90/0_2/90/0_2/90/0_3/90/0] and [±45/0_2/90/0_3/90/0_3/90/0_2] respectively through optimization. Comparison chart of two times of optimization results is shown in Fig. 8. As shown in Fig. 8, the buckling pressure is 1.8651MPa which is bigger 13% than last optimization result.

Tsai-Wu failure factor graph of the vehicle after two times of optimization is shown in Fig. 9. As shown in Fig. 9, the maximal Tsai-Wu failure factor is 0.97 which is smaller than 1, thus the vehicle's material is safe.

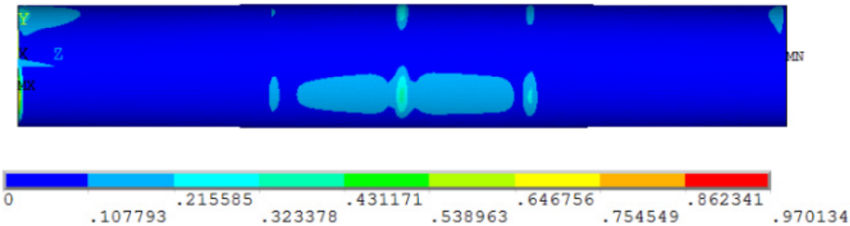

Fig. 9. Tsai-Wu failure factor graph after two times of optimization

6 Conclusion

Nonlinear number analysis method is used to study the bucking behaviors of the vehicle, well consistency with experiments is verified through an example. Buckling behaviors of three kinds of materials cylinder underwater shell is contrasted, including Carbon/Epoxy, Boron/Epoxy and Glass/Epoxy, the result shows that tensile modulus of fibers has great impact on the pressure capacity of cylindrical shell, and Carbon/Epoxy is an idea material for underwater vehicle.

The optimization of composite cylindrical shell subjected to hydrostatic pressure is investigated. Ply angle, thickness and sequence are studied using the method of distribution optimization. Buckling pressure is increased from 1.4456 to 1.8651 after two times of optimization. The buckling pressure has been greatly improved without changing shape and structure of the vehicle, saving a lot of time and energy.

References

1. Elsayed, F., Qi, H., Tong, L.L., et al.: Optimal Design Analysis of Composite Submersible Pressure Hull. Applied Mechanics and Materials **578**, 89–96 (2014)
2. Ng, R.K.H., Yousefpour, A., Uyema, M., et al.: Design, analysis, manufacture, and test of shallow water pressure vessels using e-glass/epoxy woven composite material for a semi-autonomous underwater vehicle. Journal of Composite Materials **36**(21), 2443–2478 (2002)
3. Lee, G.C., Kweon, J.H., Choi, J.H.: Optimization of composite sandwich cylinders for underwater vehicle application. Composite Structures **96**, 691–697 (2013)

4. Messager, T., Pyrz, M., Gineste, B., et al.: Optimal laminations of thin underwater composite cylindrical vessels. Composite Structures **58**(4), 529–537 (2002)
5. Hur, S.H., Son, H.J., Kweon, J.H., et al.: Postbuckling of composite cylinders under external hydrostatic pressure. Composite Structures **86**(1), 114–124 (2008)
6. Amabili, M., Karagiozis, K., Paidoussis, M.P.: Effect of Geometric Imperfections on Nonlinear Stability of Cylindrical Shells Conveying Fluid (2011)
7. Ross, C.T.F.: A conceptual design of an underwater vehicle. Ocean Engineering **33**(16), 2087–2104 (2006)
8. Kaw, A.K.: Mechanics of composite materials. CRC press (2005)
9. Hur, S.H., Son, H.J., Kweon, J.H., et al.: Postbuckling of composite cylinders under external hydrostatic pressure. Composite Structures **86**(1), 114–124 (2008)
10. Tanov, R., Tabiei, A.: A simple correction to the first-order shear deformation shell finite element formulations. Finite Elements in Analysis and Design **35**(2), 189–197 (2000)
11. Messager, T., Pyrz, M., Gineste, B., et al.: Optimal laminations of thin underwater composite cylindrical vessels. Composite Structures **58**(4), 529–537 (2002)
12. Handbook of genetic algorithms. Van Nostrand Reinhold, New York (1991)
13. Genetic Algorithms and Their Applications: Proceedings of the Second International Conference on Genetic Algorithms. Psychology Press (2013)
14. Harp, S.A., Samad, T.: Optimizing neural networks with genetic algorithms. In: Proceedings of the 54th American Power Conference, Chicago, vol. 2 (2013)
15. Carvelli, V., Panzeri, N., Poggi, C.: Buckling strength of GFRP under-water vehicles. Composites Part B: Engineering **32**(2), 89–101 (2001)
16. Barbero, E.J.: Introduction to composite materials design. CRC press (2010)
17. Tsai, S.W., Wu, E.M.: A general theory of strength for anisotropic materials. Journal of Composite Materials **5**(1), 58–80 (1971)
18. Tsai, S.W.: Theory of composites design. Think composites, Dayton (1992)
19. Groenwold, A.A., Haftka, R.T.: Optimization with non-homogeneous failure criteria like Tsai–Wu for composite laminates. Structural and Multidisciplinary Optimization **32**(3), 183–190 (2006)