Mechanical behavior of composite ship structures with open-hole

Xiaowen Li, Zhaoyi Zhu, Yan Li, Qinglin Chen and Xiaoying Zhang

School of Marine Engineering, Jimei University, Xiamen 361021, China

Email: lxwaza@163.com

Abstract. Composite materials, as advanced structural and functional materials, are increasingly used in naval and civilian fields. There are different structures with open-hole in the ship hull. The open-hole damages the continuity of the composite structure and has a direct impact on the strength and stability of the composite structure. Therefore, it is of great significance to study the mechanical behavior of composite ship structures with open-hole to ensure the safety of the ship. Based on the numerical method, the mechanical behavior of the typical composite ship structures with open-hole was investigated, and the critical buckling load, buckling mode, post-buckling behavior, ultimate bearing capacity and stress concentration of the composite structures with open-hole were analyzed. The Hashin failure criterion and complete unloading failure model were used to analyze the nonlinear buckling behavior of different composite structures with open-hole. The results show that the ultimate bearing capacity of the composite structures with typical open-holes such as rectangle, rhombus, ellipse and circle is more than 2 times of its critical buckling load, this proves that the composite structures with open-hole can have a certain bearing capacity after initial buckling. Compared with the same scale structure without open-hole, the critical buckling load and ultimate bearing capacity are reduced by about 10% and 50%, respectively. The influence of various open-holes and layer thickness on the mechanical behavior of composite ship structures is estimated through the parametric study, which provides an effective reference for the design optimization and performance evaluation of composite ships.

1. Introduction

As a new type of functional/structural material, advanced composite has a series of advantages such as light weight, high specific strength/stiffness, corrosion resistance, anti-fatigue and insulation, and the application of composite in the marine field is increasing [1-3]. It is inevitable for composite ships to have structures with open-hole in different forms and functions. The open-hole damages the continuity of composite structures and has a very important influence on the strength and stability of the structure. Statistics show that many failures of ship structures occur in the area near the open-hole, which causes stress concentration and reduces the ultimate bearing capacity of the structure [4]. Therefore, it is very important to study the mechanical behavior of composite ship structures with open-hole to ensure ship safety. Considering the weight and cost requirements, although the ratio of strength and modulus of the composite structures is high, they are usually designed to be thin-walled structures. And the composite structures with open-hole prone to buckling and post-buckling damage under six degree of freedom motion of the ship, which will seriously affect the stability and safety of the hull.

Structural stability and safety are important issues in hull structural design, which have always been highly valued by ship structural mechanics workers. Hull structure is not damaged immediately
after instability, but can continue to bear. The maximum load that the structure can bear after instability is the ultimate bearing capacity. Scholars at home and abroad have made many studies on the stability and ultimate strength of traditional stiffener panels [1, 5-7]. The mechanical behavior of metal stiffener panels has been systematically studied in many industries and a breakthrough has been made [8, 9]; Composite stiffener panels have also been widely used and developed in the fields of aviation, aerospace and automobile manufacturing [10-15]. In recent years, in the face of ship development needs on lightweight, green and multi-function, composite stiffener panels, especially the composite structures with open-hole, as the complex thin-walled structures, their stability and safety become more important. The mechanical behavior study of composite structures has also made achievements [2-3, 7, 16], but further research is needed from the perspective of composite itself and ship practicability.

In conclusion, based on the numerical analysis method, the buckling and post-buckling, stress concentration and the ultimate bearing capacity of the composite ship structures with open-hole under a dangerous working condition have been investigated. The influence of various open-holes and layer thickness on the mechanical behavior of composite structures was predicted. The paper provides an effective method for the composite ships with open-holes on the design optimization and mechanical behavior study, which can achieve a balance of weight and strength in the course of ship design.

2. Typical composite ship structure with an open-hole

2.1. Geometry of the typical composite ship structure with an open-hole

![Figure 1. Geometric configuration and dimensional parameters of the structure with a rectangle-hole.](image)

| Property                              | Symbol | Value (mm) | Remark          |
|---------------------------------------|--------|------------|-----------------|
| Total length of the panel             | $W$    | 1500       |                 |
| Width – 1 of the panel                | $L_1$  | 600        |                 |
| Width – 2 of the panel                | $L_2$  | 500        |                 |
| Transverse stiffener spacing          | $W_2$  | 300        |                 |
| Distance between the transverse stiffener and the edge of the panel | $W_3$  | 150        |                 |
| Length of the open-hole               | $W_1$  | 300        |                 |
| Width of the open-hole                | $L_3$  | 240        |                 |
| Corner radius of the open-hole        | $R$    | 30         |                 |
| Layer thickness of the panel          | $T_1$  | 0.8        | Stacking sequence |
| Layer thickness of the stiffeners     | $T_2$  | 0.8        | [0/90/±45]$s$  |
| Stiffener’s height                    | $H_2$  | 30         |                 |
The composite structure with open-hole is cut from the side structure of a composite ship, which is composed of a panel and six longitudinal and transverse reinforced stiffeners (Figure 1). It is the most common structural unit in composite ships. See Table 1 for specific size parameters.

2.2. Material property of the typical composite ship structure with an open-hole

When creating a finite element model of a structure, the first step is to set the material properties. The panel and reinforced stiffeners of the composite structure were prepared from graphite/epoxy prepreg. In order to ensure the accuracy of numeric calculation, relevant literatures were consulted, and the material properties were determined as shown in Table 2[10].

| Property                                                      | Symbol | Value   |
|---------------------------------------------------------------|--------|---------|
| Elastic modulus in 1 principal material direction             | $E_1$  | 130.0 GPa |
| Elastic modulus in 2/3 principal material direction           | $E_2/E_3$ | 10.0 GPa  |
| Shear modulus in 1-2 and 1-3 principal material planes       | $G_{12}/G_{13}$ | 4.85 GPa |
| Shear modulus in 2-3 principal material planes               | $G_{23}$ | 3.62 GPa |
| Poisson’s ratios                                              | $\mu_{23}$ | 0.31    |
| Tensile strength in fiber direction                           | $X_T$  | 1.933 GPa |
| Compressive strength in fiber direction                       | $X_C$  | 1.051 GPa |
| Tensile strength in transverse direction                     | $Y_T$  | 51 MPa   |
| Compressive strength in transverse direction                 | $Y_C$  | 141 MPa  |
| Shear strength                                                | $S$    | 61 MPa   |

2.3. Finite element model of the composite ship structure with an rectangle-hole

The Finite element model of composite structure with a rectangle-hole was established in Abaqus (Figure 2). The mesh density of the finite element model has a great influence on the analysis results. Especially for large deflection nonlinear problems, as the mesh density increases, the analysis results will converge to a unique solution, but the time required for calculation will also increase. In order to improve the analysis efficiency, according to the existing numerical conditions and simulation accuracy requirements, the plane continuous shell element is used to discretize the model. Composite panel and reinforced stiffeners were simulated by 4-node shell element (S4R). The element using linear interpolation allows finite film strain and large rotation angle. And the element taking into account the effect of shear deformation, is suitable for geometric and material nonlinear analysis. The whole model has a total of 4,845 nodes and 4,695 units, with reinforced stiffeners and the panel as common nodes.

![Figure 2. The finite element model of the composite structure with a rectangle-hole.](image)
2.4. Boundary conditions of the composite ship structure with an rectangle-hole

The ship will be subjected to a variety of loads during the voyage, resulting in multiple structural deformation. For example, the side panel is often affected by axial tension, compression and shear, as well as lateral forces and water pressure. Considering the position and function of composite stiffened panel with open-hole in the side structure, the boundary conditions are designed as side panel under compression load. In particular, one end of the panel is rigidly fixed, the other end is loaded with a displacement load of 0.4mm/s along the X-axis, and the other two sides are free edges. The specific boundary conditions are as follows: \(x=0, \ u_{x/y/z}=\theta_{x/y/z}=0\). \(x=L, \ u_{y/z}=\theta_{x/y/z}=0\). Therein, \(u_{x/y/z}\) and \(\theta_{x/y/z}\) represent the displacement and rotation degree in the global coordinate system \((x, y, z)\), respectively.

3. Basic theory

3.1. Linear buckling

Linear buckling is based on the linear elastic theory of small displacement and small strain, and it does not consider the change of structure configuration during loading. In each stage of external force application, an equilibrium equation is always established on the initial configuration of the structure. When buckling occurs, the configuration of the structure suddenly jumps to another equilibrium state. Linear buckling is also known as branching buckling or eigenvalue buckling, and the corresponding buckling load can be determined by the following linear generalized eigenvalue equation [17].

\[
([K_0] + \lambda[K_s])\{U\} = 0
\]

Where, \([K_0]\) is linear stiffness matrix of the structure; \([K_s]\) is the geometric stiffness matrix of the structure; \(\lambda\) is load scaling factor; \([U]\) is the lateral displacement vector.

Therefore, the linear stability of the structure becomes an eigenvalue problem. The critical buckling loads and buckling instability modes can be obtained by solving the eigenvalues and eigenvectors. Buckle algorithm is applied to analyze linear eigenvalue buckling in Abaqus.

3.2. Post buckling

Although eigenvalue buckling analysis can obtain linear buckling loads and buckling modes quickly, other methods are still needed to deal with geometric and material nonlinear stability problems. In this paper, the buckling problem is treated as an explicit dynamic problem. This method can adapt to complex models and has a good convergence effect.

The explicit dynamics procedure performs a large number of small time increments efficiently. An explicit central-difference time integration rule is used; each increment is relatively inexpensive (compared to the direct-integration dynamic analysis procedure available in Abaqus/Standard) because there is no solution for a set of simultaneous equations. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment, \(t\), the accelerations calculated at time \(t\) are used to advance the velocity solution to time and the displacement solution to time.

Based on the existing material failure criteria and failure evolution methods in Abaqus, the analysis is carried out. The material failure criterion is Hashin criterion. The failure energy of the fiber in the direction of tension/pressure is 12.5 N/mm, while the failure energy in the transverse tension/pressure is 1.0 N/mm.

4. Mechanical behavior prediction

4.1. Linear buckling analysis of the composite ship structure with different open-holes

In order to further study the influence of different open-holes on the mechanical behavior of composite structures, the structures with rhombus, ellipse and circle hole were designed on the basis of the rectangle hole. These open-holes have the same geometric center and area as the rectangle hole. The size parameter of the rectangle hole is 300x240xR30mm. The size parameters of the other three holes are 300x236xR50xR10, 383x235mm and R150mm, respectively.
Through linear buckling analysis, the first order buckling mode of four composite structures with different open-hole and without open-hole was obtained, as shown in Figure 3. The critical buckling loads of the above structures are 41.10kN, 41.03kN, 41.35kN, 40.31kN and 45.75kN, respectively. By comparing the above critical buckling loads, it is found that the critical buckling load of the structures with different open-hole is approximate. And the critical buckling loads were smaller than the structure without open-hole, reducing by about 10.16%, 10.32%, 9.62% and 11.89%, respectively. This indicates that the open-hole affects the stability of composite structures, and the influence degree of different open-holes is different. In contrast, the circle hole has the largest influence, followed by the rhombus hole, and the ellipse and the rectangle hole have slightly influence. In addition, the first order buckling mode of the four different open-holes are similar to the structure without open-hole, which are bounded by the longitudinal stiffener, with a 1/4 wave at the top and bottom, and the maximum out-of-displacement occurs at the center of the bottom edge. The reason is that the structure is not symmetrical, and the open-hole makes the stress transfer discontinuous, resulting in a small out-of-displacement on the other side of the structure, thus presenting the deformation mode as shown in Figure 3.

![Figure 3. The deformation of the structures with open-hole under the first order buckling mode.](image)

4.2. Nonlinear buckling and ultimate bearing capacity analysis of the composite ship structure with different open-holes

Based on the eigenvalue buckling analysis, the nonlinear buckling analysis was carried out to obtain the force and displacement curves of the composite structures with different open-hole, as shown in Figure 4. The mechanical response curves of the structures with rectangle, rhombus, ellipse and circle hole are basically the same. The boundary between linear and nonlinear is obvious. When the axial load increased to 42 kN (near the critical buckling load), the force and displacement curves appeared obvious inflection point, the slope of the curves decreased, the compressive stiffness of the structures changed. The structure can continue to carry, until the load increased to 106 kN (near the ultimate bearing capacity). There is a significant reduction in the force and displacement curve, and the composite structures with open-hole collapsed. However, the failure of fiber and matrix was not found in the structures. The reason is that the stress state of fiber and matrix at this time had not reached the level of the Hashin criteria, and the fundamental reason for the collapse of the composite thin-walled structures in this paper is that the axial geometric deformation is too large. The ultimate bearing capacity of the four composite structures with open-hole is about 108.31kN, 103.45kN, 108.74kN, and 103.00kN, respectively, all of which is more than twice of their critical buckling load. This indicates that the composite structures with open-hole still has certain compressive capacity after buckling. In addition, compared with the structure without an open-hole, the ultimate bearing capacity is reduced by about 44.93%, 47.33%, 44.63% and 47.55%, respectively. Thus, it can be seen that the effect of different open-hole on the ultimate strength of composite structures is great, and the influence degree is circle > rhombus > rectangular > ellipse.
4.3. Influence factors analysis

In order to further analyze the mechanical behavior of composite structure with different open-holes, the influence of parameters such as open form and layer thickness on mechanical properties such as stress concentration, buckling and post-buckling was investigated, which will provide references for the design optimization and practical application of composite hull structure.

4.3.1. Open-hole. The ship needs to set different open-hole in different positions of the hull structure, such as rectangle holes on the deck, rhombus and circle holes on the side, so that the complex thin-walled structures with multiple open-holes is formed inside the ship. Due to the sudden change in geometry and the weakening of the cross section of the hull caused by the open-hole, a great stress concentration will be generated near the opening when the ship travels in waves. The stress concentration will damage the hull structure and affect the safety of the ship. Therefore, in order to ensure the strength of the hull, it is necessary to make a detailed analysis of the stress concentration phenomenon at the open-hole, so as to take certain protective measures when necessary. In order to study the effect of different open-hole on the mechanical behavior of composite structures, four typical marine opening forms, namely rectangle, rhombus, ellipse and circle, were designed. And the stress concentration factor \( K \) is defined as follows.

\[
K = \frac{\sigma_{\text{max}}}{\sigma_o}
\]

(2)

Where, \( \sigma_{\text{max}} \) is the maximum stress in the area around the open-hole; \( \sigma_o \) is the stress at the geometric center of the composite structure with an open-hole.

Figure 5 shows the stress distribution of different open-hole structures. The stress near the open-hole is approximately symmetrical with the symmetry of the geometric structure, and the stress concentration is severe in the upper and lower sides. Among them, the maximum stress of rectangle and rhombus hole structure is located at the lower left corner of the hole, and the maximum stress of ellipse and circle hole structure is located at the center of the lower edge of the hole. The stress concentration coefficients of different open-hole structures are shown in Figure 6, and the value of \( K \) is between 1.63 ~ 2.08. The stress concentration coefficient of ellipse hole is the largest, followed by circle and rhombus, and rectangle hole is the smallest. It can be seen that for stress concentration alone, the structure hopes to obtain a smaller stress concentration. Therefore, the rectangle-hole structure is better than the other three holes.

![Figure 4](image_url)
4.3.2. Layer thickness. Figure 7 and Figure 8 show the influence of the change in layer thickness on the mechanical behavior of composite structures with different open-hole. The values of layer thickness are 0.4, 0.6, 0.8, 1.0 and 1.2mm. It can be seen from Figure 7-8 that the critical buckling load and the ultimate bearing capacity of the four types of open-holes, namely rectangle, rhombus, ellipse and circle, have the same variation trend, both of which increase with the increase of layer thickness. And the ultimate bearing capacity of the composite structures is more sensitive to the change of layer thickness. Compared with the original structure without an open-hole, the influence of different open-holes on the critical buckling load is less than the influence on the ultimate bearing capacity, but the influence degree is the same under different thicknesses, both are circle > rhombus > rectangle > ellipse. Thus it can be seen that the increase of the layer thickness is beneficial to the critical buckling load and ultimate bearing capacity of the composite structures with open-holes. And the ellipse-hole has little effect on the mechanical behavior of composite structures. However, in the actual design process, the weight and cost of the hull structure should be taken into consideration, and the layer thickness and structural holes should be reduced as far as possible to save cost and ensure the safety of the hull structure.
5. Conclusions

As a typical structural form of ship structure, composite structures with open-hole are prone to buckling and stress concentration during operation, and still have certain bearing capacity after instability. The buckling, post-buckling and stress concentration of the composite structures with open-hole have important effects on the stability and safety of the ship. In this paper, linear buckling and post-buckling analysis can provide reasonable prediction for the buckling behavior and ultimate strength of composite marine structures at different stages. The results of the study are as follows:

(a) The critical instability values of the composite structures with open-hole based on area equivalence are approximate and are all smaller than the critical buckling load of the one without open-hole. This indicates that the open-hole affects the stability of composite structures, and the influence degree of different open-hole is different.

(b) After buckling analysis, it was found that the main reason for the collapse of the composite structure was the large axial geometric deformation, rather than the damage of the fiber and matrix. In addition, the ultimate bearing capacity of the four different open-hole structures is more than 2 times of the critical buckling load, which proves that composite structures with open-hole still have certain compressive capacity after buckling. Compared with the same scale composite structure without open-hole, the structures with open-hole have a greater influence on its ultimate strength, and the influence degree is circle > rhombus > rectangle > ellipse.

(c) Based on the stress concentration coefficient K, the stress concentration phenomenon of four different composite structures with open-hole were analyzed. The stress concentration coefficient of ellipse-hole is the largest, followed by circle and rhombus, and rectangle-hole is the smallest. It can be seen that for stress concentration alone, the structure hopes to obtain a smaller stress concentration coefficient. Therefore, the rectangle-hole structure is better than the other three ones.

(d) The critical buckling load and the ultimate bearing capacity of the four structures with different open-hole, have the same variation trend. And the ultimate bearing capacity of the composite structures is more sensitive to the change of the layer thickness. Compared with the original structure without open-hole, the influence of different open-holes on the critical buckling load is less than the influence on the ultimate bearing capacity, but the influence degree is the same. Thus it can be seen that the increase of the layer thickness is beneficial to the critical buckling load and ultimate bearing capacity of the composite structure with open-holes. However, in the actual design process, the weight and cost of the hull structure should be taken into consideration, and the layer thickness and structural holes should be reduced as far as possible to save cost and ensure the safety of the hull structure.
**Acknowledgments**

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51909103) and the Natural Science Foundation of Fujian Province of China (Grant No. 2018J05090, 2018J05089 and 2018J01493).

**References**

[1] Yu Hui Chen Zhipeng Zhou Yun et al 2017 Optimal design of integrative superstructure in composite materials *Shipbuilding of China* **58**(02) 30-37

[2] Li Xiao Wen Shao Fei Zhu Zhaoyi et al 2018 Design and strength test of lightweight T joints for ships *Journal of ship mechanics* **22**(04) 454-463

[3] Kolanu N R Raju G Ramji M 2018 Experimental and numerical studies on the buckling and post-buckling behavior of single blade-stiffened CFRP panels *Composite structures* 196

[4] Wang Xun 2009 Strength and buckling analyses of ship girders with cutout *Wuhan university of technology*

[5] Chen Yanting Yu Changli Gui Hongbin 2017 Research development of buckling and ultimate strength of hull plate and stiffened panel *Chinese journal of ship research* (1)

[6] Xu M C Soares C G 2012 Numerical assessment of experiments on the ultimate strength of stiffened panels *Engineering structures* 45

[7] Zhao W Xie Z Wang X et al 2019 Buckling behavior of stiffened composite panels with variable thickness skin under compression *Mechanics of advanced materials and structures* 1-9

[8] Ghavami K Khedmati M R 2006 Numerical and experimental investigations on the compression behaviour of stiffened plates *Journal of constructional steel research* **62**(11) 1087-1100

[9] Khedmati M R Bayatfar A Rigo P 2010 Post-buckling behaviour and strength of multi-stiffened aluminium panels under combined axial compression and lateral pressure *Marine structures* **23**(01) 39-66

[10] Kong C W Lee I C Kim C G et al 1998 Postbuckling and failure of stiffened composite panels under axial compression *Composite structures* **42**(1) 13-21

[11] Song Gang Cui Degang Dong Lijun 2017. Application of buckling/post-buckling analysis for composite stiffened panels *Acta materiae compositae sinica* (1)

[12] Zhu S Yan J Chen Z et al 2015 Effect of the stiffener stiffness on the buckling and post-buckling behavior of stiffened composite panels *Composite structures* **120** 334-345

[13] Mo Y Ge D He B 2016 Experiment and optimization of the hat-stringer-stiffened composite panels under axial compression *Composites part B: engineering* **84** 285-293

[14] Tan Xiangfei He Yuting Feng Yu et al 2018 Stability and post-buckling carrying capacity of aeronautical composite stiffened panel under shear loading *Acta materiae compositae sinica* **35**(02) 320-331

[15] YB SudhirSastry Pattabhi R Budarapu N Madhavi et al 2015 Buckling analysis of thin wall stiffened composite panels *Computational materials science* **96** 459-471

[16] Anyfantis K N, Tsouvalis N G 2012 Post Buckling Progressive Failure Analysis of Composite Laminated Stiffened Panels *Applied composite materials* **19**(3) 219-236

[17] Chen N Z Soares C G 2006 Buckling Analysis of Stiffened Composite Panels// III European Conference on Computational Mechanics *Springer netherlands*