To cite this article: LIU J J, DING Z, MA L, et al. Steel model test on structural strength of ship superstructure underoverall longitudinal bending [J/OL]. Chinese Journal of Ship Research, 2022, 17(2). http://www.ship-research.com/en/article/doi/10.19693/j.issn.1673-3185.02240.

DOI: 10.19693/j.issn.1673-3185. 02240

Steel model test on structural strength of ship superstructure under overall longitudinal bending

LIU Junjie[*1], *DING Zhen*[2], *MA Lin*[1], *BIAN Xin*[1], *LI Zhengjie*[1]

1 China Ship Scientific Research Center, Wuxi 214082, China

2 Shanghai Division, China Ship Development and Design Center, Shanghai 201108, China

Abstract: [**Objectives**] The superstructure participates in the overall longitudinal bending of a ship, which leads to stress concentration in certain parts and threatens the safety of the ship's structure. The large-scale steel model test can truly reflect the structural response characteristics of superstructures. [**Methods**] This paper studies the structural strength of a certain ship's superstructure. Through the equivalent simplification of the main hull structure, a large-scale steel model including the superstructure and main hull is designed, and a structural strength model test is carried out under hogging moment load. [**Results**] The test and FE calculation results show obvious stress concentration phenomena in the corners of the side openings of the superstructure and the edges of the round transitions between the sidewall and main deck. The bending effectiveness of the superstructure is 0.315. [**Conclusions**] The results of this study can provide references for the local structural strengthening and optimal superstructure design of target ships. The simplified design method of the ship hull model provided in this paper can also serve as a reference for the design of large-scale ship models.

Keywords: superstructure; structural strength; stress concentration; steel model test; bending effectiveness

CLC number: U661.43

0 Introduction

The structural strength of the superstructure that houses important cabins, such as the pilothouse, command room, and crew accommodation, of large ships is vital to the structural safety and combat capability of the ships. All about the bearing capacity of the superstructure when it participates in the overall longitudinal bending of the ship, the structural strength of the superstructure has long been the focus of the shipbuilding industry. Considering the continuous distribution of the main hull structure of the ship in the longitudinal direction, the hull girder theory is typically adopted to calculate the overall longitudinal strength of the hull structure[1]. However, the superstructure is usually shorter than the ship, which causes the discontinuity of the hull structure, ultimately resulting in obvious stress concentration. Crawford put forward the double girder theory, i.e., assuming that the main hull and the superstructure exist in the form of separate girders and bear horizontal and vertical forces respectively and then calculating the normal stress, deflection, and curvature of the two girders on this assumption [2]. Pei et al. [3] analyzed the interaction between the main hull and the superstructure of a passenger ship in an inland river in light of the double girder theory and studied the effectiveness of

Received: 2020－12－24 **Accepted:** 2021－03－26

Supported by: High-Tech Ship Foundation of Ministry of Industry and Information Technology (Gongxinbulianzhuang [2016] No.25)

Authors: LIU Junjie, male, born in 1978, Ph.D., professor
DING Zhen, male, born in 1983
MA Lin, male, born in 1980, master degree, senior engineer
BIAN Xin, male, born in 1989, master degree, engineer
LI Zhengjie, male, born in 1980, master degree, senior engineer

***Corresponding author:** LIU Junjie

the superstructure's participation in the overall longitudinal bending. Qian [4] proposed a simplified model for evaluating the effectiveness of the superstructure, and this model, simplifying the three-dimensional (3D) structure of the hull into a two-dimensional (2D) model, well simulates the interaction between the superstructure and main deck structure, and simplifies the calculation of the level of the superstructure's participation in the overall longitudinal bending of the hull. He et al. [5] used the finite-element (FE) method to analyze the stress concentration at the end of the superstructure of a certain model of a ship and calculated its stress concentration factor.

Some scholars also used the FE method to study the structural strength of the superstructure and its influence on the overall strength of the hull [6-8]. Although this method enables the simulation of the geometry of the hull structure and efficient calculation of the stress distribution of the superstructure under ideal stress, it cannot directly reflect the stress response and deformation characteristics of the typical parts and structures under the load. For this reason, corresponding tests need to be carried out to study the stress distribution characteristics of the structure. Li [9] carried out model test on the structural strength of the superstructure built with composite materials but adopted the truncated model of the cabin for the test, which poses great difficulty in simulating the boundary conditions and loading mode of the model.

Accordingly, with the forecastle superstructure of a ship as the research object, a large-scale model test is conducted on the structural response of its typical parts when the ship's hull bears the overall longitudinal hogging moment, and the test results are analyzed to support the optimization of the ship's structure.

1 Model similarity and structure simplification

1.1 Model similarity

The model test in this paper is mainly designed to study the stress distribution characteristics of the superstructure under overall longitudinal bending. Therefore, the test model should meet the geometric similarity requirement in structure. Besides, the test load needs to satisfy the similarity criterion to evaluate the bending moment on the full-scale ship. Moreover, the test model should adopt the same materials as those of the full-scale ship to ensure that the same stress level as that in the case of the full-scale ship under the corresponding load can be obtained through the model test. The basic physical quantities describing material properties include Young's modulus E, shear modulus G, and Poisson's ratio μ. Generally, the two independent physical quantities E and μ are selected to describe the material properties of the structure.

Because the scale of the hull structure, which is a box-girder thin-walled type of structure, and the thickness of the hull plate are at different magnitudes, the geometric similarity requirement cannot be fully satisfied when a scale model is used to test the strength of steel structures, in which case different scale ratios can be used. A large-scale steel model is adopted to minimize the influence of the scale effect on the test results, and the scale ratios adopted are as follows: The scale ratio for the main scale $\lambda_L = 1:4$ and that for plate thickness $\lambda_t = 1:2$. The calculation formula for the normal stress of structural bending is $\sigma = Mz/I$, where, for the overall longitudinal bending of the hull, M represents the vertical bending moment on the cross-section of the hull; z is the distance between the stress point to be solved of the superstructure and the neutral axis; I is the vertical moment of inertia of the cross-section to the neutral axis. According to the similarity theory, the similarity between the model and the full-scale ship in the section characteristics at the same measuring position can be obtained:

$$\begin{cases} \dfrac{I_m}{I_s} = \lambda_L^3 \lambda_t \\ \dfrac{z_{nm}}{z_{ns}} = \lambda_L \end{cases} \tag{1}$$

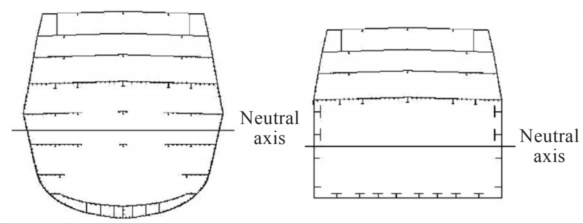
where I_m and I_s are the vertical moment of inertia on the section of the model and the full-scale ship respectively, and z_{nm} and z_{ns} are the height of the vertical neutral axis of the model and the full-scale ship respectively.

For equal stress at the same location under the overall longitudinal bending, the bending moment M_m applied in the model test and the corresponding bending moment M_s in the case of the full-scale ship should meet the following similar requirements:

$$\frac{M_m}{M_s} = \lambda_L^2 \lambda_t \tag{2}$$

1.2 Structure simplification

In this paper, the cabin section of the hull including the forecastle superstructure is selected as the design object of the test model. Given the high main hull within this section, however, the model height would be too large if the scale ratio for the main scale given above was adopted. Moreover, the variety of internal components of the main hull not only leads to a significant increase in the processing cost of the model but also poses challenges to its transportation and assembly. Considering that the model test is mainly designed to study the stress distribution of the superstructure, the main hull structure needs to be simplified. The profile characteristics of the simplified hull structure should be similar to that of the full-scale ship, so that the distribution characteristics of the stress on the section of the superstructure under the overall longitudinal bending moment will not be affected. For this reason, the box girder is used to replace the main hull, with its upper surface as the main deck of the hull and the superstructure on the main deck completely retained. All hull components are scaled down according to the scale and plate thickness of the full-scale ship by the above scale ratios. Specifically, if the steel plates at the relevant thickness cannot be purchased directly in the market after some side longitudinals are scaled down by the given scale ratio for plate thickness, these side longitudinals can be made of steel plates at a similar thickness. Then, the scale of the side longitudinals is adjusted to the extent that the cross-sectional area of the side longitudinals after adjustment is equal to that after scale reduction. In this way, a structural response of the deck under the vertical bending moment of the hull generally the same as that in the real situation can be ensured. According to the calculation formula for the overall longitudinal bending stress of the hull $\sigma_x = M_z/I_y$, the distance z between the superstructure of the simplified structure and the neutral axis and the moment of inertia I_y on the section should be both the same as those in the case of the full-scale ship to ensure that the stress distribution characteristics of the superstructure are the same as those of the superstructure of the full-scale ship. The hull structure under the main deck can be simplified by the following method: With several typical sections of the cabin section of the target ship hull as the benchmark, the rectangular box girder is used to replace the main hull, with no need to follow completely the above principle for scale reduction. The height of the box girder is set to 8.5 m (2.215 m after scale reduction), and its width is the same as that of the main deck. The above constraints can be met by adjusting the plate thicknesses of the side and bottom plates of the box girder, arranging flat steel and T-shaped steel stiffeners on the side and bottom, and adjusting the scale and plate thicknesses of the stiffeners. The section structure at the same frame before and after simplification is presented in Fig. 1.



(a) Structure of full-scale ship (b) Equivalent structure

Fig. 1 Comparison of main hull structure before and after equivalent simplification

2 Test model and loading method

The four-point bending loading method is adopted according to the demand of the test on the applied load, as well as that of the capacity and location of the loading equipment of the laboratory. The whole superstructure at the bow of the target ship is 29.5 m long, and the cabin section of the hull that contains this superstructure is selected as the test section. This cabin section has a full-scale length of 35 m, a maximum width of 16.33 m, and a maximum height of 14.8 m. A steel test section model is designed according to the full-scale structure of the target ship together with the above model scale ratios by the above equivalent structure simplification method, and it has a length of 8.75 m, a maximum width of 4.08 m, and a maximum height of 3.64 m. Moreover, 3 m loading sections at both ends of the model are designed to obtain the corresponding pure bending load in the model test section. Besides, a transition section is set between the test section and the loading ones to save the stress response at both ends of the test section from the concentrated load applied in the test. According to the calculation, two loading sections 2.375 m long can not only meet the required test accuracy but also satisfy the demand of the location of the test equipment. Fig. 2 presents the overall segmentation of the model (the unit of the values in the figure is mm). The transition and loading sections are symmetrically distributed at both ends. The overall model length is 20 m, and the specifical scales from one end to the other are "0.25 m (local reinforcement at the load application points at both ends) + 3 m (loading section) + 2.375 m (transition section) + 8.75 m (test section)

+ 2.375 m (transition section) + 3 m (loading section) + 0.25 m (local reinforcement at the load application points at both ends)". The steel material of the model test section is the same as that of the full-scale ship, with a nominal yield strength of σ_s = 315 MPa. The transition sections and the loading ones are made of steel with a yield strength of σ_s = 345 MPa. The overall weight of the whole test model is about 49 t.

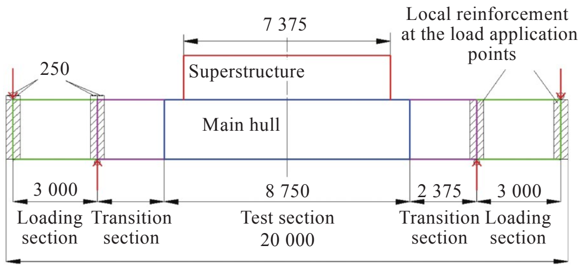


Fig. 2 Overall distribution of test model

The loading system used in the model test is presented in Fig. 3, containing loading and fixing devices. Specifically, the loading device is divided into a contact device, a loading beam, and two oil pressure cylinders, among which the contact device is used in coordination with the loading beam and the oil pressure cylinder transmits the load to the model through the loading beam and the contact device. The fixing devices are composed of a reaction frame, a reaction beam, and a contact device, among which the reaction beam, as simple support for the model, is mainly designed to prevent significant deformation at both ends of the model under extreme loading conditions. Considering that the load in the model test does not cause significant deformation of the model, the reaction beam is not used. Due to the large mass of the test model itself, the model is laid flat (the starboard side of the hull faces the ground) to steer clear of the influence of the model gravity on the stress measurement. Moreover, pulleys are utilized as the support between the main hull and the ground to reduce the friction between them, and loading is then performed at the bottom of the model (hull bottom) to simulate the structural response of the superstructure when the hull is in the hogging state under pure bending load (Fig. 4).

3 Test measurement and data processing method

Guided by the test purpose, strain gauges are used to measure the structural response of typical

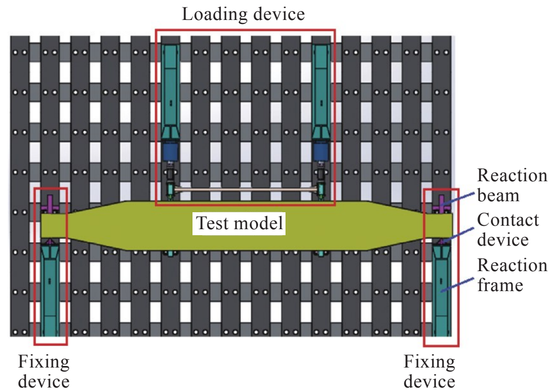


Fig. 3 Test loading system

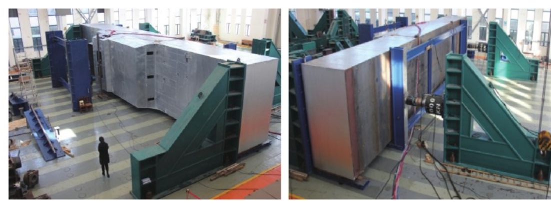


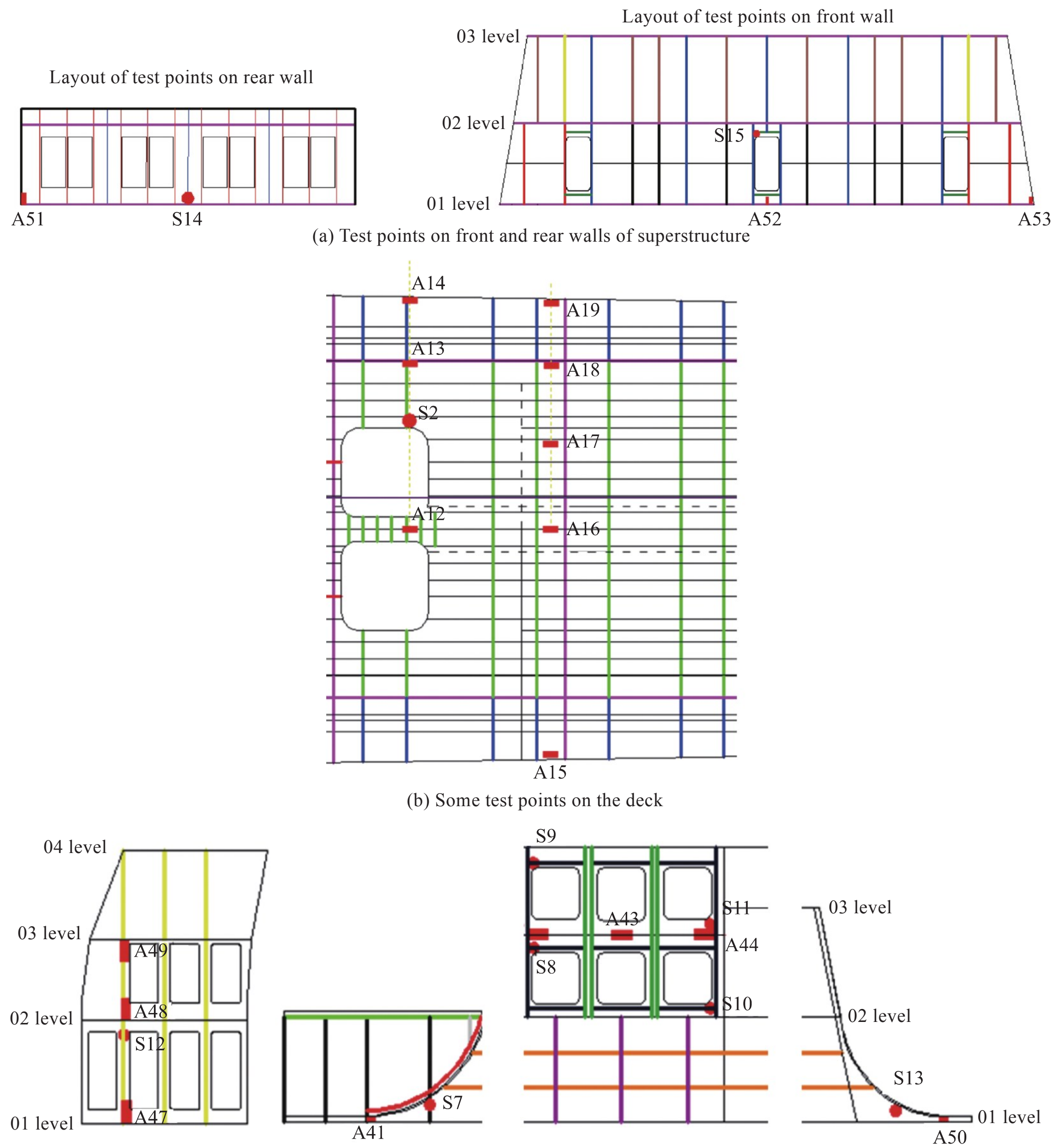
Fig. 4 Model state before test

parts of the superstructure under the hogging bending moment. The locations of test points are mainly selected according to the FE calculation results of the ship and arranged at high-stress points and typical locations, including the opening corners of the front and rear walls and the root of the superstructure (Fig. 5(a)), the opening corners and typical locations on the decks at each layer of the superstructure (Fig. 5(b)), the opening corners and typical locations on the sidewalls of the superstructure, and the arc transition section connecting them with the main deck of the hull (Fig. 5(c)). A total of 72 test points of strain are arranged, including 15 three-way points with their number starting with "S" and 57 one-way points with their number beginning with "A". Fig. 5 shows the locations of some test points.

The strain at each test point can be directly measured through the test. However, it needs to be converted into stress if the stress response characteristics of the superstructure are to be analyzed. In the test, one-way strain gauges are used at some test points, such as the joints between the superstructure and the main deck of the hull featuring a clear direction of the principal stress (the principal stress comes in the vertical direction). Three-way strain gauges are used at other test points, e.g. the opening corners. When a one-way strain gauge is used, the stress at the corresponding test point can be calculated according to Hooke's law:

$$\sigma_x = E\varepsilon_x \tag{3}$$

Regarding the strain measured by the three-way



(a) Test points on front and rear walls of superstructure

(b) Some test points on the deck

(c) Some test points on superstructure sidewalls and in the arc transition sections of the bow and the stern

Fig. 5 Some test points

strain gauges, the von Mises equivalent stress at the test point needs to be calculated by the following formula. The longitudinal, transverse, and shear strains ε_x, ε_y, and γ_{xy} obtained by the three-way strain gauges can be expressed as

$$\varepsilon_x = \varepsilon_{0^\circ}, \quad \varepsilon_y = \varepsilon_{90^\circ}, \quad \gamma_{xy} = 2\varepsilon_{45^\circ} - \varepsilon_{0^\circ} - \varepsilon_{90^\circ}$$

where ε_{0°, ε_{45°, and ε_{90° are the positive strain measured at 0°, 45° and 90° respectively. The corresponding longitudinal, transverse, and shear strains σ_x, σ_y, and τ_{xy} can be expressed as

$$\sigma_x = \frac{E}{1-\mu^2}(\varepsilon_x + \mu\varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\mu^2}(\varepsilon_y + \mu\varepsilon_x)$$

$$\tau_{xy} = \frac{E}{2(1+\mu)}\gamma_{xy} \tag{4}$$

The principal stress at the test point where a three-way strain gauge is used can be expressed as

$$\begin{pmatrix}\sigma_1\\ \sigma_2\end{pmatrix} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

The von Mises equivalent stress σ_e at such a test point is

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2}$$

or

$$\sigma_e = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \tag{5}$$

4 Test result analysis

4.1 Analysis of stress concentration in superstructure

Under the hogging bending load, the maximum stress in the superstructure occurs at the test point S12 (three-way gauge), which is an opening corner on the sidewall near the stern end located at the vertical tangent of the upper corner of the second opening forward at the sidewall tail of the chimney on the larboard of the superstructure of the target ship (Figs. 5(c) and 6). When the test load (i. e., the thrust of a single oil cylinder) reaches 263.6 t, the von Mises equivalent stress at this test point reaches 356.6 MPa (Fig. 7), exceeding the nominal yield stress of the material. Fig. 7 indicates that when the test load is about 125 t, the stress variation curve undergoes obvious nonlinear changes at this test point, and similar situations are reported at some other test points, despite that the test load when such a case occurs is different. Observation shows that such situations all occur at the test points close to weld seams. The closeness of the test points to the weld seams may explain this phenomenon: When the test load reaches a certain value, the release of the residual stress near the weld seams affects the stress at the test points during welding.

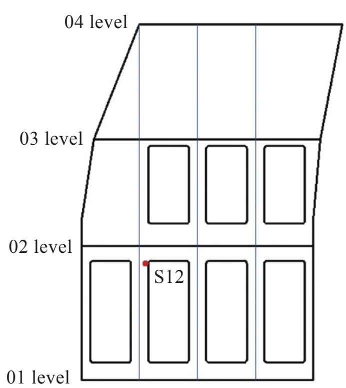


Fig. 6 Location of test point S12

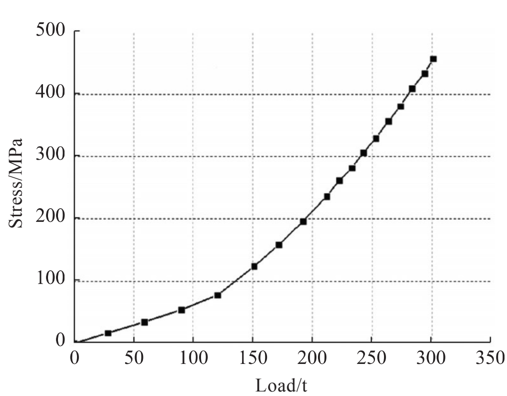


Fig. 7 Variation of von Mises equivalent stress at test point S12 with load

Fig. 8 shows the FE calculation results under a test load of 263.6 t. It indicates that the location of the maximum stress in the superstructure is the same as that in the test results: The FE calculation result is 345 MPa, with a 3.25% deviation from the test result. The high stress in the superstructure sidewall openings of the ship is mainly in the opening corner between the main deck and 02 level, and the remarkable stress concentration here calls for local reinforcement or design optimization.

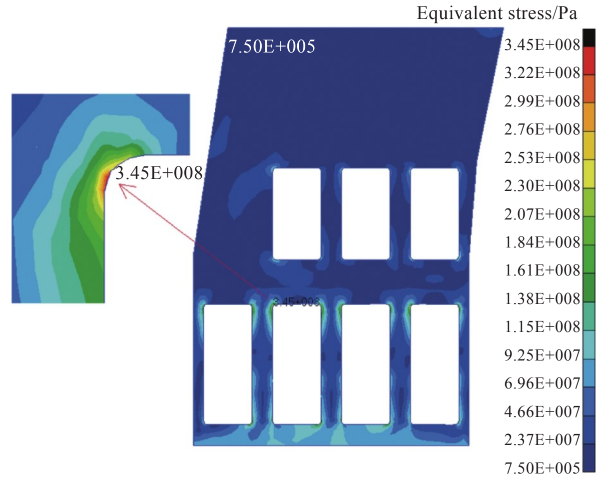


Fig. 8 FE calculation results of superstructure sidewall openings

The analysis of the test results reveals that significant stress concentration also occurs on the transition arc connecting the sidewall of the superstructure and the main deck. Fig. 9 presents the variation curves of the von Mises equivalent stress at the test points in the arc transition sections of the bow and the stern. It shows that the difference between the stress at the test points in the arc transition sections of the bow and the stern is insignificant. When the test load reaches a specified value, the stress at the test point in the bow becomes slightly larger than that in the stern: The stress at test point S13 in the bow is 118.87 MPa, and that at test point S7 in the stern is 111.0 MPa. The FE calculation results are shown in Fig. 10, which indicates that the results of the comparison of stress concentration points in the bow with those in the stern obtained by FE calculation are the same as those obtained by the model test: The stress in the bow is invariably larger than that in the stern, with the numerical results obtained

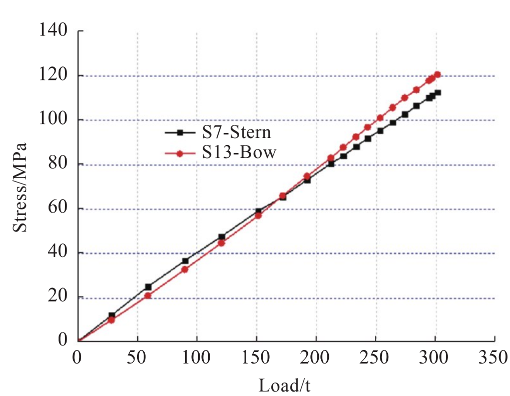


Fig. 9 Variation of equivalent stress at test points in arc transition section connecting superstructure sidewall with main deck

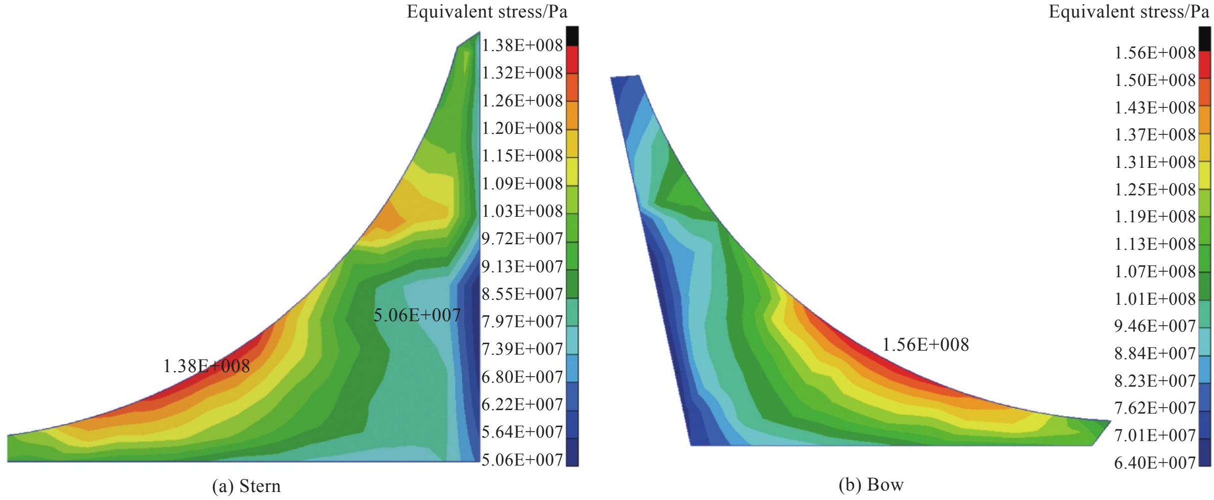


Fig. 10 FE calculation results of arc transition section connecting superstructure and main deck

by the model test smaller than the FE calculation results. This can be explained by the fact that the weld seam between the web of the arc transition section and the panel affects the layout of the test points, causing the space between the test points and the edge of the arc and ultimately preventing the measurement of the maximum stress value at the stress concentration point.

4.2 Analysis of effectiveness of superstructure's participation in overall longitudinal bending

According to Reference [10], a calculation formula for η, the effectiveness of the superstructure's participation in the overall longitudinal bending of the ship hull, is given by

$$\eta = \frac{\sigma_0 - \sigma_p}{\sigma_0 - \sigma_{100}} \tag{6}$$

where σ_0 represents the stress in the main deck with no regard to the superstructure, MPa; σ_p is the actual calculated stress in the main deck of the hull, MPa; σ_{100} is the stress in the main deck when the superstructure is 100% effective, MPa. In this paper, the effectiveness of the superstructure is calculated on the middle frame section of the superstructure in the cabin section of the hull of the test object. According to the formula $\sigma_x = M_z/I_y$, the superstructure (the structure on the main deck) is removed, i.e., only the main hull part is left, in the calculation of σ_0. Corresponding to the above section, the vertical moment of inertia $I_{y\,\text{main hull}}$ on the section and the height $Z_{n\,\text{main hull}}$ of the neutral axis are calculated, thereby obtaining the vertical distance Z_1 between the main deck and the neutral axis. The vertical bending moment is set to that under the corresponding test load, and $\sigma_0 = 79.4$ MPa is obtained by the theoretical calculation method. σ_p is set to the longitudinal stress measured by the test corresponding to that at test point A16 (Fig. 5 (b)) at the intersection of the cross-section and the middle longitudinal section on the main deck, i.e., $\sigma_p = 66.53$ MPa. σ_{100} is calculated in a way similar to that by which σ_0 is calculated, except that the corresponding section adopted for calculation needs to be the one containing the superstructure. $I_{y\,\text{whole}}$ is used as the vertical moment of inertia on the section, and $Z_{n\,\text{whole}}$ is adopted as the height of the neutral axis. Then, the vertical distance Z_2 between the main deck and the neutral axis is thereby obtained, and $\sigma_{100} = 38.58$ MPa is acquired by theoretical calculation. According to Equation (6), the effectiveness of the superstructure of the ship can be calculated as $\eta = 0.315$.

5 Conclusions

With the forecastle superstructure of a ship as the research object, this paper simplifies the main hull by the equivalent structure method and designs a steel scaled model of a cabin section containing the whole forecastle superstructure and the main hull. Then, the four-point bending loading method is employed to study the superstructure, particularly its stress concentration and the effectiveness of its participation in the overall longitudinal bending, under the hogging bending moment. The main conclusions drawn are as follows:

1) Opening groups occur on the superstructure sidewall of the ship, and obvious stress concentration is observed in the opening corner between the main deck and 01 level. When the test load reaches 263.6 t, the von Mises equivalent stress at a test point in the opening corner hits up to 356.6 MPa, exceeding the nominal yield stress of the material.

In this case, the structure of this part needs to be reinforced or optimized.

2) Stress concentration is also observed at the arc edge near the bottom part of the arc transition sections in the bow and the stern connecting the sidewall of the superstructure with the main deck. The study shows that under the same load, the values measured by the test are smaller than those obtained by FE calculation, which can be largely explained by the denied installation of the strain gauge onto the arc edge that results in the deviation in the location of the test point.

3) The effectiveness of the participation of the forecastle superstructure in the overall longitudinal bending of the hull is 0.315.

4) Many factors are behind the deviation between the test results and the FE calculation results. For instance, the idealized FE model gives no regard to the influence of the defects in the actual hull structure on the strength of the local structure. Besides, the processing accuracy of the model and the deviation in the installation locations of the strain gauges also act on the test results. Despite the deviation between the two results, they reflect consistent structural response characteristics, and the model test can more truly reflect the strength characteristics of the structure of the full-scale ship.

References

[1] YANG D S. Hull strength and structural design [M]. Beijing: National Defense Industry Press, 1986: 40−68 (in Chinese).

[2] SUN C. Research on the effects of superstructure in longitudinal strength of inland ship [D]. Harbin: Harbin Engineering University, 2013 (in Chinese).

[3] PEI Z Y, MA Z Y, ZHU B, et al. Research on the bending efficiency of superstructure to hull girder strength of inland passenger ship [J]. Ocean Engineering, 2020, 195: 106762.

[4] QIAN R J. A simplified model of ship superstructure for its effectiveness analysis [J]. Journal of Shanghai Jiao Tong University, 1996, 30 (10): 99−103 (in Chinese).

[5] HE Z P, WANG F H, WANG D Y. Analysis and photoelastic test on the stress concentration of superstructure end and broadside with large opening [J]. Shipbuilding of China, 2006, 47 (1): 84−89 (in Chinese).

[6] YANG L, ZHANG S X. On the boundary conditions for FE analysis of the ship's superstructures [J]. Ship & Ocean Engineering, 2004 (1): 18−20 (in Chinese).

[7] YE B Z, YE Z M. The application of superstructure validity analysis on the strength calculation of some ship [J]. Guangdong Shipbuilding, 2005 (4): 12−14 (in Chinese).

[8] ZHANG Y C, WANG Z L, LUO G E. FE analysis of the complete lifting and mounting strength of ship superstructure [J]. Ship Engineering, 2006, 28 (3): 62−65 (in Chinese).

[9] LI Y K. Research on mechanical properties of composite superstructure and test method of typical model [D]. Harbin: Harbin Engineering University, 2018.

[10] PLA General Equipment Department. Method for structural design and strength calculation of naval surface ships: GJB/Z 119-99 [S]. Beijing: PLA General Equipment Department, 1999 (in Chinese).

总纵弯曲下舰船上层建筑结构强度钢模试验

刘俊杰*[1]，丁震[2]，马琳[1]，卞鑫[1]，李政杰[1]
1 中国船舶科学研究中心，江苏 无锡 214082
2 中国舰船研究设计中心，上海 201108

摘　要：［**目的**］上层建筑会参与船体总纵弯曲，从而导致特殊部位的结构产生应力集中现象，对舰船结构安全造成威胁，而大尺度钢模试验则能较为真实地反映上层建筑的结构响应特征。［**方法**］为此，以某舰艏楼上层建筑为研究对象，通过对主船体进行结构等效简化，设计包含整个上层建筑和主船体在内的大尺度舱段缩比钢质模型，并开展中拱弯曲下的结构强度模型试验。［**结果**］试验结果和有限元计算结果的对比分析表明，在目标舰上层建筑舷侧开口群角隅，以及上层建筑侧壁与主船体连接的圆弧过渡段上，均存在明显的应力集中现象，上层建筑参与总纵弯曲的有效度为0.315。［**结论**］研究成果可为目标舰上层建筑局部结构加强或优化设计方案的制定提供参考，所建立的船体模型简化设计方法也可为舰船大尺度钢模试验模型的设计提供参考。

关键词：上层建筑；结构强度；应力集中；钢模试验；弯曲有效度