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Similarity Criterion and Scale Effect for Ship Distortion Model Under Combined Loads

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Abstract: For the ultimate strength model test evaluation of large ship structures, the distortion model with non-uniform ratio between the main size and the plate thickness size is usually adopted. It is the key to carry out scale model test to establish a distortion model similar to the real ship structure under combined load. A similarity criterion for ship distortion model under the combined action of bending moment and surface pressure was proposed, and the scale effect for the criterion was verified by a series of numerical analysis and model tests. The results show that the similarity criterion for ship distortion model under combined loads has a certain scale effect. For the model tests of ship cabin structures, it is suggested that the scale range between the plate thickness scale and the main dimension scale should be controlled within 2:1, which can be used as a reference for distortion model design and ultimate strength test of large-scale ship structures.

Key words: distortion model; combined load; similarity criteria; scale effect; ultimate strength test

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0 Introduction

Scale model test is one of the important means to accurately evaluate the ultimate strength of large ship structures. For large ships, the ship length is usually more than 80 meters, and the width and depth can reach over 10 meters. The thickness of main load-bearing structures such as main deck and bottom plates is usually 8~20 mm, and the main dimensions of cabin length, width and height are much larger than the thickness. Therefore, in the ultimate strength test of model structure, the distortion model with an unequal ratio of main dimension to plate thickness is generally used. At present, the evaluation method of ultimate strength of ship structure based on model test is still being developed and improved. On one hand, various surface pressures on the ship structure, such as hydrostatic pressure, slamming in waves and cargo load, will induce the buckling of local grids and affect the structural failure mode. However, under the combined action of bending moment and surface pressure, the similarity between the ultimate strength performance of the model and the real ship structure is not clear[1-2]. On the other hand, in practical application, it is found

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that the distortion models with different scale ratios are quite different from the nonlinear structural response characteristics of the real ship in a certain range. The ultimate strength and failure mode obtained from the model test may not accurately reflect the real performance of the real ship structure. Therefore, the similarity analysis between distortion model and real ship under combined load has become one of the important directions of ship structural strength test and evaluation.

In recent years, some researchers have made a lot of progress in structural distortion model similarity theory and model test research. Tanaka et al[3] obtained the change law of ultimate strength of typical container ship cabin under the combined action of bending moment and torque by carrying out distortion model test under multiple working conditions. Cheng[4] analyzed the continuous collapse process of typical hull beams under the action of torque, and put forward a similar relationship to characterize the ultimate torsional strength of twisted models. Wang et al[5] put forward the similarity relation of hydrostatic pressure load on the bottom based on the equivalent bending moment method, and verified it by model calculation of many typical ship structures. Zhang et al[6] improved the relationship between model distortion degree and mesh length scaling method, and established the selection method of mesh length scaling ratio of distortion model. Song[7] carried out a series of numerical and experimental analysis of ultimate strength of stiffened plates and box girder structures under scale combination, and found that nonlinear similarity has the influence of scale effect.

However, the similarity criterion and size effect of distortion model under complex loads are rarely involved. In the present paper, the similarity criterion of ship distortion model under the combined action of bending moment and surface pressure is put forward, and the scale effect of the criterion is verified by a series of numerical analysis and model tests. The variation characteristics of the ultimate strength deviation with scale ratio are obtained, and the suggestion of scale range between plate thickness scale ratio and main scale ratio is given. The related research results can serve as a reference for the development of structural similarity theory and ultimate strength model test technology.

1 Similarity criterion for distortion model under combined loads

For large-scaled models, it is necessary to solve the following three similarity problems to accurately establish the similarity relationship between the distortion model and the real ship structure under combined loads.

(1) The transition from single load similarity to combined load similarity

In the actual navigation of a ship, the hull mainly bears the bending moment, while the bottom below the waterline also bears the local influence of water surface pressure. Based on the similarity relation of distortion model of stiffened plate under axial compression load (see Fig. 1), the

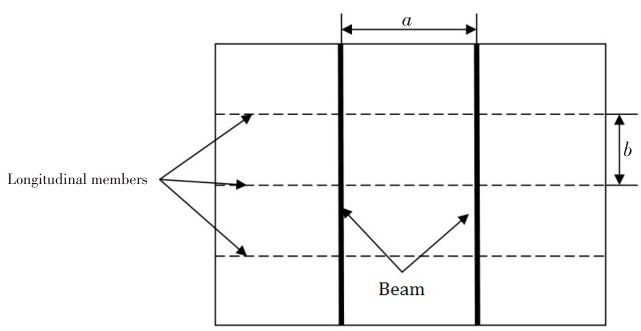


Fig.1 Typical stiffened plate

similarity relation of distortion model of ship structure under simple bending moment is deduced. Based on the equivalent ultimate bending moment, the similarity relation of ship structure distortion model under simple surface pressure is deduced[3], and the effectiveness of the two similarity relations under the combined action of bending moment and surface pressure is further presented.

(2) Similar transition from linear stage to nonlinear stage

If the ultimate strength model test of ship structure is to be carried out, it is necessary to ensure that the distortion model is similar to the structural response of the real ship in the online elastic stage and nonlinear stage, so as to effectively reflect the performance characteristics of the real ship structure failure in the whole process. The traditional directional dimension analysis method satisfies the stress similarity of ship structure in linear elastic stage through the similarity relation of inertia moment. It is necessary to establish the similarity between the starting point and the end point of the nonlinear stage to realize the similarity of the nonlinear stage.

(3) The local structural response is similar to that of the whole structure

As the nonlinear state of the distortion model is similar to that of the real ship, the failure modes of the two should be basically the same, that is, the model can effectively reflect the failure and collapse process of the real ship structure from the local to the whole. By establishing the design method of local members, the distortion model has the same compression flexibility coefficient as the real ship's plate frame and longitudinal members, which ensures the similarity of local overall failure modes. The calculation formula of the two coefficients is

$$\beta = \frac{b}{t_d}\sqrt{\frac{\sigma_Y}{E}} \tag{1}$$

$$\gamma = \frac{a}{r}\sqrt{\frac{\sigma_Y}{E}} \tag{2}$$

where, β is the compression compliance coefficient of the lattice, γ is the compression compliance coefficient of the longitudinal member. a is the grid length, b is the width of the grid, t_d is the plate thickness, E is the elastic modulus, σ_Y is the yield strength and r is the radius of gyration of longitudinal members with plates.

Based on the recent achievements of authoritative research institutions in the field of ship structure model test technology, such as Shanghai Jiao Tong University, Wuhan University of Technology and China Ship Science Research Center, the similarity criterion expression for ship structure distortion model under the combined action of bending moment and surface pressure is established as follows:

$$\begin{cases} \lambda_\sigma = 1 & \left(\lambda_I = \lambda_L^3\lambda_t\right) \\ \lambda_M = \lambda_L^2\lambda_t\lambda_{\sigma Y} & \left(\lambda_\beta = \lambda_\gamma = 1\right) \\ \lambda_P = \dfrac{\lambda_t}{\lambda_L}\lambda_{\sigma Y} & \end{cases} \tag{3}$$

where, λ_σ is the stress scale ratio of linear elastic state, λ_M is the scale ratio of bending moment, λ_P

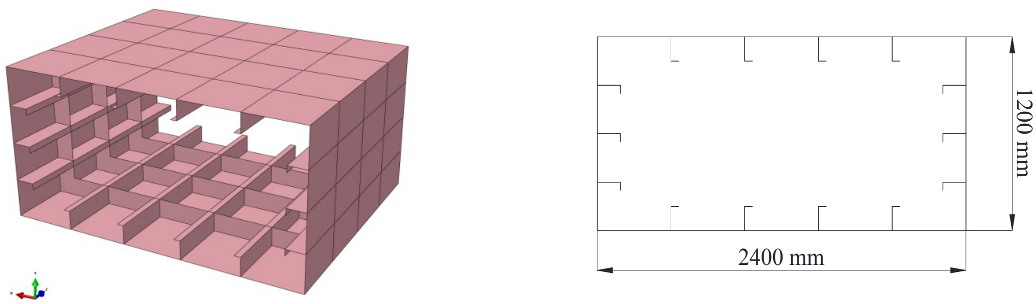
is the scale ratio of surface pressure, λ_L is the main dimension scale ratio, λ_t is the scale ratio of plate thickness, $\lambda_{\sigma Y}$ is the scale ratio of material's yield strength, λ_I and λ_β are the scale ratios of the cross-sectional moment of inertia of the cabin and the compression compliance coefficient of the lattice, and λ_γ is the scale ratio of compression compliance coefficient of longitudinal members.

2 Scale effect of similarity criterion for distortion model under combined loads

In order to verify the accuracy of similarity criterion of distortion model under combined loads and explore its scale effect range, a set of box girder prototype and corresponding distortion models are designed based on various scale combinations, and a series of ultimate strength analysis and typical test verification of similar model under combined load are carried out.

2.1 Box girder structure

The prototype box girder structure has a total width of 2400 mm and a total height of 1200 mm. The single-span slab is 480 mm long and 12 mm thick. L-shaped longitudinal beams with the same size of 150 mm × 50 mm are arranged on the deck, side plates and bottom plate, as shown in Fig.2.



(a) 3D model (b) Cross section type

Fig.2 Prototype box girder structure

According to the similarity criterion, to ensure the value $\lambda_\beta=1$, the number of longitudinal members in distortion model will decrease, but there is at least one longitudinal member on the deck. What's more, the minimum plate thickness specification for arc welding is 3 mm. So the scale range of the principal dimension of the distortion model is set to 1/2–1/10, and the scale range of the plate thickness is set to 1/1.5–1/4. A total of 17 distortion models are designed in Tab.1. The positions and sizes of the longitudinal members of each model are optimized. The flexibility coefficient of the prototype deck panel is 1.5265, and that of the distortion model deck panel is between 1.1448 and 1.5265. Both prototype and distortion models are made of Q235 steel.

Tab.1 Main size design and surface pressure load of prototype and distortion models

Model	λ_L	λ_t	Grid length /mm	Total width /mm	Total height/ mm	t/mm	Number of deck longitudinal members	β	Surface pressure P/MPa
Prototype	1	1	480	2400	1200	12	4	1.5265	0.100
No.1 distortion model	1/2	1/1.5	240	1200	600	8	3	1.4311	0.133
No.2 distortion model	1/3	1/1.5	160	800	400	8	2	1.2721	0.200

Tab.1 (Continued)

Model	λ_L	λ_t	Grid length /mm	Total width /mm	Total height/ mm	t/mm	Number of deck longitudinal members	β	Surface pressure P/MPa
No.3 distortion model	1/3	1/2	160	800	400	6	3	1.2721	0.150
No.4 distortion model	1/4	1/1.5	120	600	300	8	1	1.4311	0.267
No.5 distortion model	1/4	1/2	120	600	300	6	2	1.2721	0.200
No.6 distortion model	1/4	1/3	120	600	300	4	3	1.4311	0.133
No.7 distortion model	1/5	1/1.5	96	480	240	8	1	1.1448	0.333
No.8 distortion model	1/5	1/2	96	480	240	6	1	1.5265	0.250
No.9 distortion model	1/5	1/3	96	480	240	4	2	1.5265	0.167
No.10 distortion model	1/5	1/4	96	480	240	3	3	1.5265	0.125
No.11 distortion model	1/6	1/2	80	400	200	6	1	1.2721	0.300
No.12 distortion model	1/6	1/3	80	400	200	4	2	1.2721	0.200
No.13 distortion model	1/6	1/4	80	400	200	3	3	1.2721	0.150
No.14 distortion model	1/8	1/3	60	300	150	4	1	1.4311	0.267
No.15 distortion model	1/8	1/4	60	300	150	3	2	1.2721	0.200
No.16 distortion model	1/10	1/3	48	240	120	4	1	1.1448	0.333
No.17 distortion model	1/10	1/4	48	240	120	3	1	1.5265	0.250

The box girder structure model bears both the bending moment of the middle arch and the uniform surface pressure on the bottom plate. The pressure load on the surface of the prototype bottom plate is 0.1 MPa, and the surface load of the corresponding distortion models are calculated according to the similarity criterion. The design parameters and surface pressure load value P of prototype and distortion models are summarized in Tab.1.

2.2 Numerical simulation of ultimate strength

The quasi-static method is used to carry out nonlinear numerical simulation analysis of the ultimate strength of the box girder structure prototype and distortion models. The large-scale general numerical simulation software ABAQUS 6.14 is used for modeling and simulation analysis. The prototype and distortion models are adopted along the longitudinal direction, and the single span and its front and rear 50% length range are modeled. Four-node reduced integral shell element is used for modeling, and mesh division ensures that the number of mesh in the width direction of longitudinal component panel is not less than four. The Young's modulus of elasticity E is 206 GPa, Poisson's ratio ν is 0.3 and the yield strength σ_y is 300 MPa.

The surface pressure load is evenly distributed on the outer surface of the base plate of prototype and distortion models according to Tab.1. Rigid points are arranged at the centroids of the longitudinal ends of the structure and are rigidly connected with the end faces. The X direction is along the length direction of the structure, the Y direction is along the width direction, and the Z direction is along the height direction. Simply supported boundaries are set at rigid points at both ends of the structure, and both ends satisfy $UY = UZ = RX = RZ = 0$ and $UX = 0$ respectively. Meanwhile, an increasing equivalent reverse angle RY is applied to the hard points at both ends to simulate the middle arch loading state.

The bending moment-rotation curves of the box girder prototype and distortion models converted to the prototype are shown in Fig.3. The sag deformation morphology of the limit state is shown in Fig.4. The results show that:

(1) In the linear elastic stage, the moment-rotation curves of the prototype and all distortion models converted to the prototype basically coincide. In the non-linear stage, the moment-rotation curves converted from the prototype and all distortion models are obviously different.

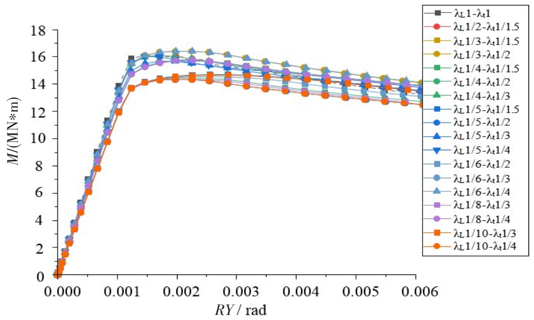


Fig.3 Moment-rotation curves of prototype and distortion models

(2) The failure modes of the prototype and all distortion models are basically the same. The failure modes are local plate buckling of bottom plate and web buckling of longitudinal members, as shown in Fig.4.

(a) Prototype　(b) No.1 distortion model　(c) No.2 distortion model　(d) No.3 distortion model

(e) No.4 distortion model　(f) No.5 distortion model　(g) No.6 distortion model　(h) No.7 distortion model

(i) No.8 distortion model　(j) No.9 distortion model　(k) No.10 distortion model　(l) No.11 distortion model

(m) No.12 distortion model　(n) No.13 distortion model　(o) No.14 distortion model　(p) No.15 distortion model

(q) No.16 distortion model　(r) No.17 distortion model

Fig.4 Vertical deformation morphology of prototype and distortion models

2.3 Model test verification

The model tests were carried out to verify the accuracy of numerical simulation results. To reflect the impact of λ_t/λ_L value on the similarity of the models, the test prototype and distortion models are designed according to the prototype of box girder structure and the design parameters of distortion models No.9, No.11 and No.12. The whole model consists of test section, transition section and loading section, as shown in Fig.5. The test section which is of the same structure as the box girder is the main assessment object of the model test. The transition section transfers the load to the test section and achieves a smooth transition of stress flow. The loading section in conjunction with the loading system is used to apply bending moments to the model. The total length of the prototype model is 17 000 mm, and the length of the test section is 1920 mm. Three sets of distortion test models meet the similarity criteria of distortion models under combined loads, and the corresponding similarity ratios are $\lambda_L = 1/5$, $\lambda_t = 1/3$; $\lambda_L = 1/6$, $\lambda_t = 1/3$ and $\lambda_L = 1/6$, $\lambda_t = 1/2$. The structures of the distortion model test section are shown in Fig.6, and the construction materials are the same as the test prototype. The main dimensions of the prototype and model of box girder structure test are listed in Tab.2. According to the processing re-inspection, the correction results of scale surface pressure load are listed in Tab.3.

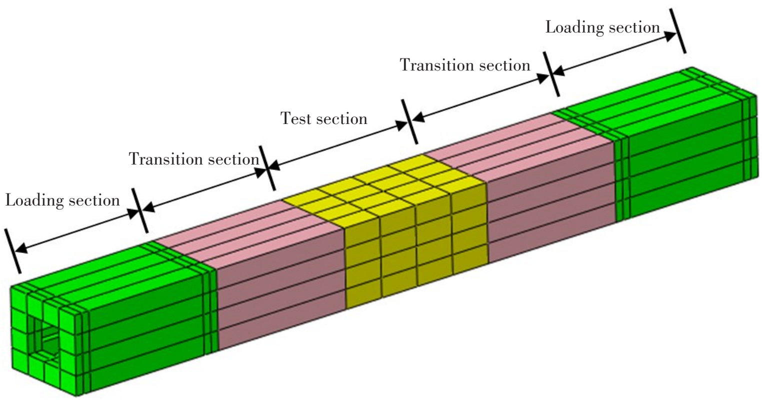
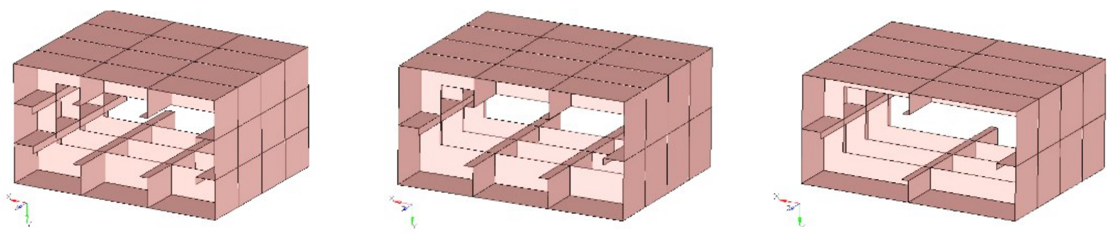


Fig.5 Schematic diagram of box beam test prototype and test model structure



(a) T1 test model (b) T2 test model (c) T3 test model

Fig.6 3D schematic diagram of test distortion models

Tab.2 Design of structural dimensions for test prototype and distortion models

Test model	λ_L	λ_t	Total length/ mm	Total width /mm	Total height /mm	Length of test section /mm	t of test section /mm	Number of deck longitudinal members	Dimensions of longitudinal members in test section /mm
Test prototype	1	1	17 000	2400	1200	1920	12	4	L150×50×12
T1 test model	1/5	1/3	5200	480	240	384	4	2	L60×20×4
T2 test model	1/6	1/3	5200	400	200	320	4	2	L50×17×4
T3 test model	1/6	1/2	5200	400	200	320	6	1	L40×13×6

Tab.3 Correction of scale ratio and surface pressure load based on model processing

Name	t in test section /mm		Measured value of λ_t	Measured value of σ_Y /MPa	$\lambda_{\sigma Y}$	P /MPa	
	Design value	Measured average				Design value	Measured value
Test prototype	12.00	12.00	1/1	316.0	1/1	0.100	0.100
T1 test model	4.00	4.18	1/2.87	262.0	1/1.21	0.167	0.144
T2 test model	4.00	4.18	1/2.87	262.0	1/1.21	0.200	0.173
T3 test model	6.00	5.73	1/2.09	242.5	1/1.30	0.300	0.221

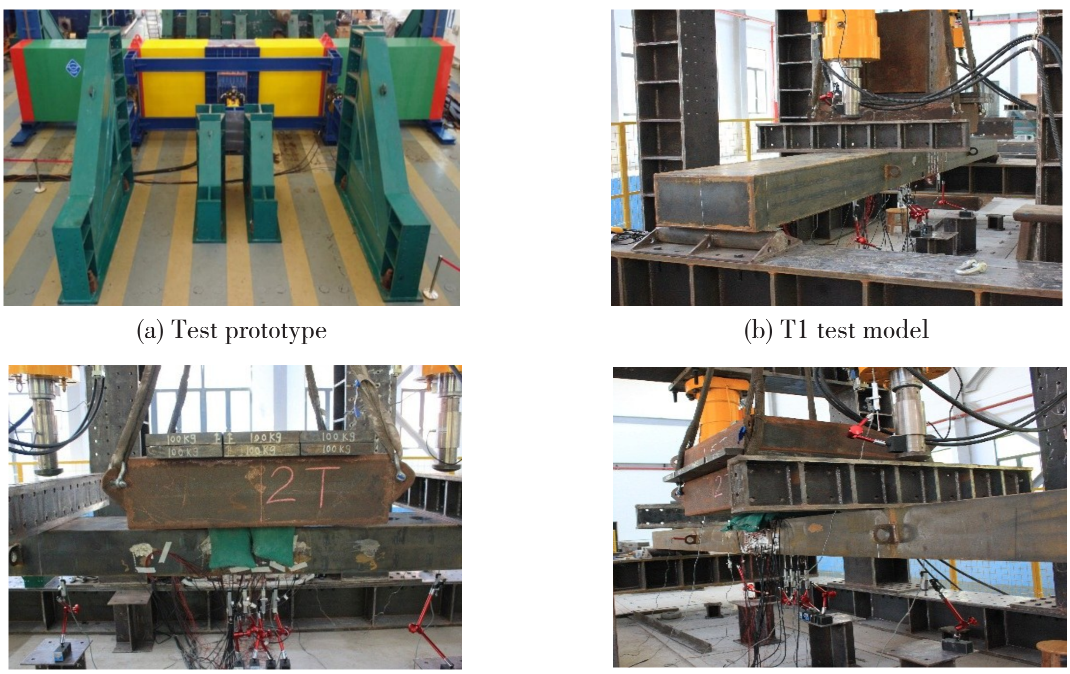
The model tests were carried out in China Ship Scientific Research Center and Shanghai Jiao Tong University. The loading scheme of ultimate strength test is as follows:

(1) The bending moment of the middle arch is loaded by four-point bending method. Two electro-hydraulic servo actuators exert concentrated force on the box between the loading section and the transition section of the structure, while at the same time two reaction frames are used to support the box outside the stressed section of the structure, thus realizing the simply supported boundary condition.

(2) Surface pressure is applied to the bottom plate of the test model. A surface loading device is applied to the prototype, and a fixed counterweight is applied to the distortion model.

The model layout and test loading site are shown in Fig.7. The ultimate loads of tests and numerical analysis for test prototype and models are summarized in Tab.4. Comparison of the ultimate failure mode of the test models with the deviation of the test model converted into the prototype ultimate load are shown in Figs.8-11. The test results show that:

(1) Compared with the above calculated values, the maximum difference between the test values of ultimate bending moment of box girder structure prototype and each distortion model is only



(a) Test prototype (b) T1 test model

(c) T2 test model (d) T3 test model

Fig.7 Test site

5.84%.

(2) The failure modes are basically the same, which are local plate buckling of bottom plate and web buckling of longitudinal members.

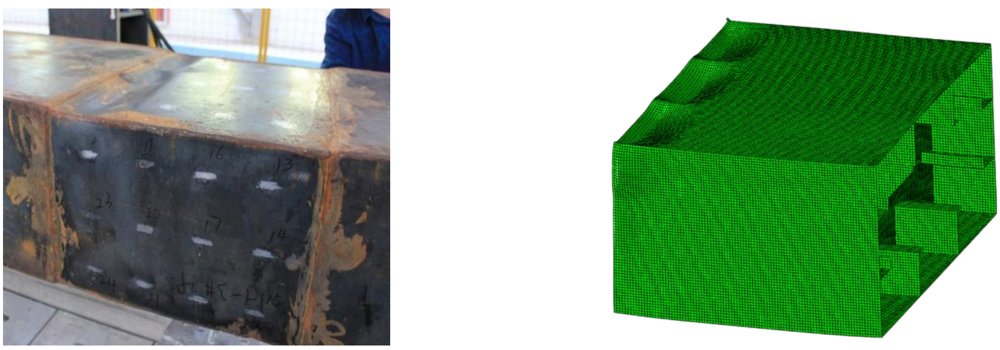
Therefore, the experimental results are close to the calculated results, which verifies the accuracy of the above numerical simulation methods.

Tab.4 Ultimate loads of tests and numerical analysis for test prototype and models

Name	Ultimate load of test (kN·m)	Ultimate load of numerical analysis (kN·m)	Difference between test and numerical analysis
Test prototype	14 677	15 334	5.84%
T1 test model	158	161	2.39%
T2 test model	109	113	3.55%
T3 test model	132	135	2.22%

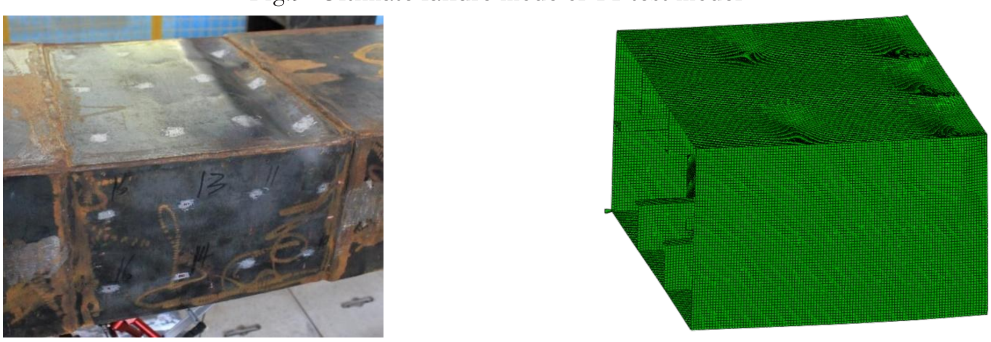
(a) Test result (b) Numerical analysis

Fig.8 Ultimate failure mode of test prototype



(a) Test result (b) Numerical analysis

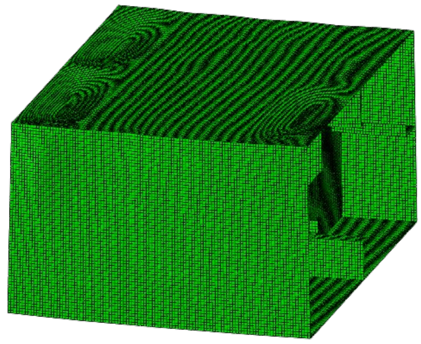
Fig.9 Ultimate failure mode of T1 test model



(a) Test result (b) Numerical analysis

Fig.10 Ultimate failure mode of T2 test model

(a) Test result



(b) Numerical analysis

Fig.11 Ultimate failure mode of T3 test model

2.4 Analysis for scale effect

After converting the ultimate load of distortion models to the prototype, the deviation between the model conversion and the prototype ultimate load can be expressed as

$$\Delta = \left| \frac{\lambda_M M_m - M_s}{M_s} \right| \tag{4}$$

where, Δ is the deviation between the model conversion and the prototype ultimate load, M_m is the ultimate load of distortion model, and M_s is the ultimate load of prototype.

After the ultimate bending moment of each distortion model is converted into the prototype, the relationship between Δ and λ_t/λ_L is shown in Fig.12 based on the numerical analysis and model test results. The deviation between the ultimate loads increases synchronously with the increase of λ_t/λ_L value. When $\lambda_t/\lambda_L>2$, the deviation is more than 8%, and the maximum is as high as 10.92% with the numerical results and 11.67% with the test results, which verifies the scale effect of similarity criterion of distortion model under combined load.

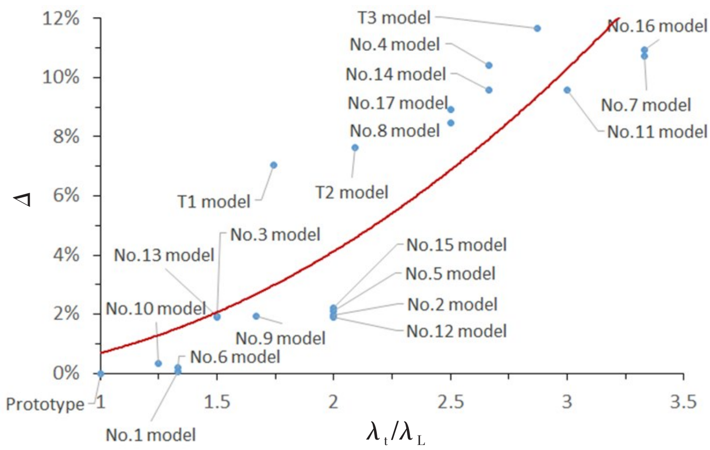


Fig.12 Relationship between Δ and λ_t/λ_L for numerical analysis and model tests

3 Concluding remarks

The similarity criterion for ship distortion model under the combined action of bending moment and surface pressure was proposed, and the scale effect for the criterion was verified by a series of numerical analysis and model tests. The results of numerical analysis and model test show that there is a certain scale effect in the similarity criterion for ship distortion model under combined loads. The deviation between the converted value of model ultimate strength and the prototype ultimate strength increases synchronously with the increase of the ratio between the plate thickness scale and the main dimension scale. For the structure designed in this paper, when the ratio exceeds 2:1, the deviation degree will exceed 8%. Therefore, when carrying out model tests on typical ship structures, it is suggested that the scale range between the plate thickness scale and the main dimension scale should be controlled within 2:1.

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复合载荷作用下船舶畸变模型相似准则及尺度效应研究

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摘要：对大型船舶结构开展极限强度模型试验评估，通常采用主尺寸与板厚尺寸非等比缩比的畸变模型，如何实现复合载荷作用下畸变模型与实船结构相似是其重要问题之一。本文提出弯矩-表面压力复合作用下船舶畸变模型相似准则，并对准则的尺度效应进行系列数值分析和模型试验验证。研究表明，复合载荷作用下船舶畸变模型相似准则存在一定的尺度效应，对舱段结构开展模型试验时，建议板厚缩尺比与主尺寸缩尺比之间的比例范围控制在2:1以内。研究成果可为大型船舶结构畸变模型设计与极限强度试验提供参考。

关键词：畸变模型；复合载荷；相似准则；尺度效应；极限强度试验

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