Structure of Anti-fatigue Design of Multi-deck Vessel: Typical Details

Huilong Ren[a], Qingyue Zhang[b], Xueyun Jiang[c], Yumeng Hu[d]

College of Ship Building Engineering, Harbin Engineering University, Harbin, 150001, Chian

[a]renhuilong@263.net,[b]120357608@qq.com,[c]771955943@qq.com,[d]704976009@qq.com

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Abstract: The fatigue strength problem of multi-deck ship is serious. When in the same external load and nominal stress level, structural fatigue life of the details are closely related to the specific structural forms. Therefore, optimizing the structure of the details could reduce the stress concentration factor of details local structure, and has an important role in improving the fatigue life of details. Based on parametric modeling approach, a method of shape optimization of multi-deck ship structure typical details was studied. In this method, APDL language was utilized to create a parametric model of a typical detail. Stress concentration factor and details shape parameter were respectively taken as the objective function and optimization variables. Computing program was written to achieve anti-fatigue design purpose. According to this method, several typical details were optimized and details structure forms with smaller stress concentration factor were given.

Introduction

As the large-scale development of ship design and excessive use of high-strength steel, the problem of fatigue strength of ship structure becomes more and more prominent. It is often found that some of the typical details could not meet the fatigue strength requirements of the specification standard in strength check, which brings great trouble to structure design. Compared to the conventional single deck ships, vessels with multi-deck structure have more varied and complex structural form, load case and sailing area. Meanwhile, in order to solve the contradiction between the structure lightweight and the structural strength, the main hull structure of vessels tend to use a lot of high-strength steel to meet its yield and buckling strength. Thus, the fatigue problem of vessels with multi-deck is more serious and should be paidsufficient attention. Corresponding anti-fatigue design in early design is effective.

Large number of theoretical studies and experimental results show that under the same external load strength and nominal stress level, the fatigue life of the structure typical details is closely related to its stress concentration factor. There are several ways to reduce the stress concentration factor of typical details in engineering. Among these ways, changing the shape of the typical details to reduce the stress concentration factor is an effective method. With the method of spectral analysis, the fatigue of a curved edge brackets is analyzed and comparison between the computation results of curved brackets and those of straight edge brackets is done in literature [1]. By the finite element program ANSYS, the load bearing capacity of the beam structural details of ship was discussed when the bracket's size changes. And three connection patterns of bottom girder were analyzed in the strength and buckling aspects in literature [2].And both literatures have achieved certain achievements. Therefore, the optimization of typical details can effectively reduce its stress concentration level, and has an important role in improving its fatigue life.

Due to the complexity of typical details of the multi-deck vessels structure, accurate assessment of the fatigue life depends on the fine mesh finite element analysis. And parametric modeling approach can quickly build and analyze series models[3]. Aimed at these problems, this paper uses finite element software ANSYS and its integrated parametric compiled language APDL to establish parametric model of a multi-deck vessel and to do the optimal computation. Anti-fatigue design of several typical details is proposed, and the results provide a reference for typical details design of multi-deck vessels.

Stress concentration factor

There are many discontinuous components in hull structure. Sectional shape of these members will suddenly mutate in some places. And those places will produce higher stress, and the gradient is large. The maximum stress at some point may even be many times larger than the average stress, which is a local phenomenon, called stress concentration. It is a common case of fatigue failure due to stress concentration. Therefore, the research of the stress concentration problems has practical significance in improving the fatigue strength of typical details structure. CCS, DNV and other major classification societies have put forward the calculation method of stress concentration factor and corresponding stress concentration factor of various typical details in their fatigue strength assessment guidelines [4-5]. Typical details form of multi-deck vessels structure is special, so it is difficult to find the corresponding form in the specification. Stress concentration factor of multi-deck vessels needs to be obtained by finite element calculation.

Stress concentration factor mentioned in this article mainly refers to geometric stress concentration factor d caused by geometry mutation. For actual calculation, the ratio of hot spot stress and nominal stress is termed the stress concentration factor, which can be represented as:

$$K = \frac{\sigma_h}{\sigma_n} \tag{1}$$

The calculation methods of hot spot stress σh of both CCS and DNV are the same. It is obtained by stress calculation result of fine mesh finite element. Specific calculations are represented as follows:

$$\sigma_{\max} = \frac{3\sigma_{t/2} - \sigma_{3t/2}}{2} \tag{2}$$

$$\sigma = C_1\sigma_1 + C_2\sigma_2 + C_3\sigma_3 + C_4\sigma_4 \tag{3}$$

Where，σt/2 and σ3t/2 can be calculated by Eqn. (3). σ1, σ2, σ3, and σ4 are stress value of four finite element nodes near the weld toe. Coefficient C1, C2, C3 and C4 are calculated as follows:

$$C_i = \frac{\prod_{j \neq i}\left(x - x_j\right)}{\prod_{j \neq i}\left(x_i - x_j\right)} \quad i=1,2,3,4 \tag{4}$$

Where, x is distance between the interpolated point and the weld toe; xi is the distance between the finite element node and the weld toe.

According to the provisions of CCS, the nominal stress could be calculated by beam theory.

Optimization model

In term of strength calculation on ship structure, it is often done according to existing scheme and then the result needs to be compared with specification to check whether it meet requirement or not. Obviously, the optimal scheme may not come through this method. The optimal scheme on a certain performance of a structure, with many conditions constrained (such as stiffness, materials, strength, craft, weight, area, volume, stress, expense and so on), is achieved by mathematic means which controls the variation of some crucial parameters including size, shape and arrangement form of structure.The proposition above can be expressed by these mathematic formulas:

$$min f\left(X\right), X \in R^n \tag{5}$$

$$g_i\left(X\right) \le 0, i = 0, \ldots, m \tag{6}$$

$$x_i^l \le x_i \le x_i^u \tag{7}$$

In the process of applying this fundamental principle to anti-fatigue design based on typical details of ship structure, design variable is apparently the shape parameter of detail structure. And state parameter could be stiffness, strength, weight, area of detail and so on, which are the constraint conditions required to meet within procedure of optimizing. Besides, the objective function could stand for the index of fatigue strength of typical details, such as stress concentration factor.

Realization of parametric modeling and fatigue design

Parametric modeling refers to a finite element modeling method whichuses variable parameters instead of constant values. The parametric geometry model of a typical detail of a multi-layer surface vessel is established by using compiled parametric APDL language in ANSYS, design parameters for the shape parameter typical detail. Meshing and the definition of material properties are on the basis of requirements of CCS fatigue specification. Loads and boundary conditions are automatically appliedto simulate the actual stress state of a typical detail. The automatic extraction the stress results and the calculation of stress concentration factor is completed in the processing platform of ANSYS.

The structure anti-fatigue design of a typical detail can be completed in the optimization design module of ANSYS. APDL language is applied to specify the critical value and property of the variables and objective function, and to optimize the tolerance of iteration and to select the appropriate the optimization algorithm to search iterations in search field. ANSYS provides users with a variety of optimization algorithms, which have their advantages and disadvantages. In this article,a sub-order algorithm problem and zero-order approximation problem are used interchangeably for the anti-fatigue design.

Results and analysis

Ship structure is divided into a number of cabins by multi-deck. In order to alleviate the high stress and stress concentration of bracket toe,soft toe form shown in Figure 1 is often used. A parametric model of this typical detailis established by APDL language. Its stress state and boundary conditions inthe case of longitudinal bending is simulated. The parametric model is presented in Figure 2 and the calculation results of stress areillustrated in Figure 3.

It could be found from Figure 3 that the intersection of the web and the panel of bracket toe appeared larger stress concentration due to geometric mutation. According to the calculation method of stress concentration factor mentioned in the first quarter, hotspot stress is computed by principal stress interpolation near the stress concentration point and nominal stress is calculated by beam theory. Interpolation points are shown in Figure 4.

Loading mode can only simulates the stress state of the details by beam theory, but cannot fully reflect the state of its external load. However,the calculation results of changing external load showthat the details stress concentration factor does not change with the altering of external load level. Within the effective range of the external load, stress concentration factor appears to be the same. As is shown in Figure 1, stress concentration factor is taken as objective function, bracket toe height H, bracket toe dip □and panel ends width b1 are taken asoptimization variables. At last, anti-fatigue design is done.

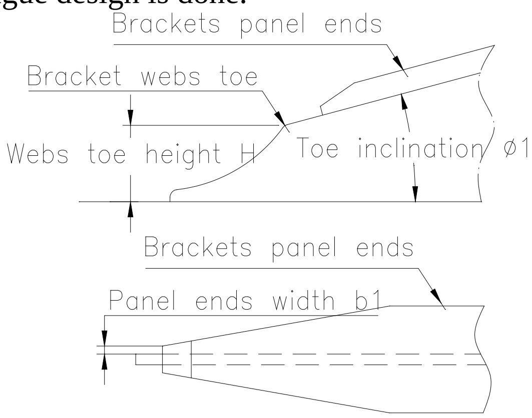

Fig. 1 Shape parameters of bracket toe

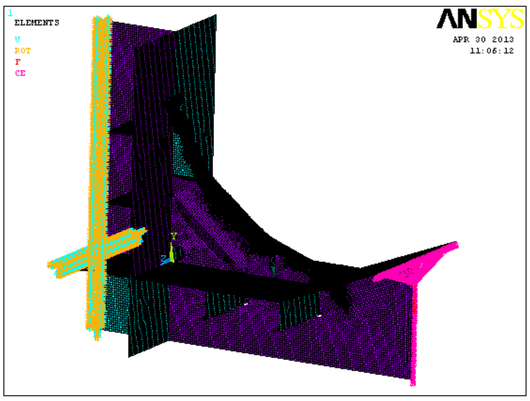

Fig. 2 Parameterized finite element model

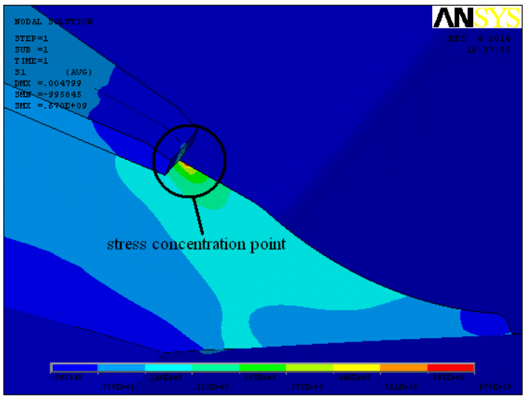

Fig. 3 Results of stress calculation

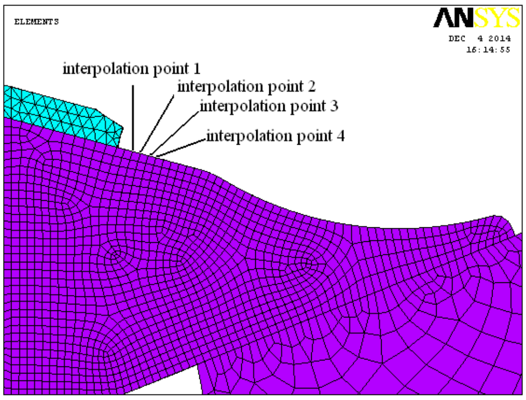

Fig. 4 Diagram of interpolation points

Optimization iterative calculation is done in ANSYS optimization design module. Comparison of shape parameters and stress concentration factor between before and after optimization is shown in Table 1.

Table 1 Parameters contrast before and after optimization

Optimization parametric	H/m	$\phi_1/(^\circ)$	b_1/m	Nominal stress(MPa)	Hotspot stress(MPa)	K
Before optimization	0.100	15.00	0.022	220.44	381.45	1.730
After optimization	0.068	12.93	0.025	232.312	370.235	1.593
Decrease rate	—	—	—	—	—	8.60%

Conclusions

In this paper, parametric modeling language APDL and ANSYS software are used to study the anti-fatigue design of typical details of multi-deck vessels. After calculation and optimization, it can be found that even the subtle changes of geometry will have a significant impact on the stress concentration factor of details. But for most of structure typical details of the ship, its form is not optimal from the reducing stress concentration factor and improving fatigue life perspective. With the anti-fatigue design method of ship structure typical details mentioned in this paper, details form with smaller stress concentration factor is obtained. The results can provide a reference for the structure design and shape optimization.

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