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Design and Simulation Analysis of Bolt Group Connection of BS-Type Flange Cast Steel Right-Angle Sea Valve

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Abstract: BS type flanged cast steel right-angle sea valve is an important valve used to stop the backflow of medium in the ship pipeline system. The valve and the pipeline are connected by a bolt connection. To ensure the reliability of the bolt connection, the theoretical calculation and finite element method are used to verify the reliability of the design of bolt connection. The theoretical result and the result of finite element analysis (using ANSYS) show that the largest stress on the bolt is located in the middle of the bolt. This paper provides solutions for the verifying the design of bolt connection in valves based on comparing the results of theoretical calculation and finite element analysis.

Keywords: Finite element analysis, right-angle outlet valve, bolt connection design

1. Introduction

The BS type flange cast steel right-angle sea valve is used as a control element in the pipeline system of ships whose medium is seawater. Its valve flap is a circular valve flap, which relies on the closure of the valve to block the backflow of the medium. The valve is connected to the pipeline by a flange connection, in which the bolt group connection plays a role in ensuring the safety and reliability of the pipeline's daily work.

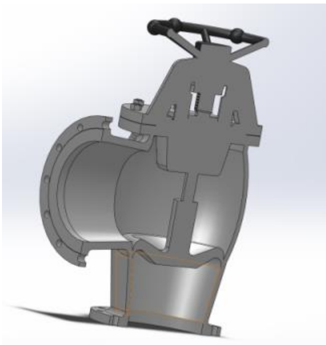

Fig. 1 - Diagram of internal section of the valve body

At present, there has been many scholars in China studied the design of bolt group connection for different working conditions. Dai Chaoqun [1] calculated the axial force of the bolt reaching the lower yield point. Based on that he designed

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the bolt connection on the cylinder head. Li Liou [2] calculated the working load on the bolts under the action of the overturning moment, and the design of the foot bolts of the storage belt bin was carried out. Li Chang [3] calculated the tensile strength and the preload of the bolts in the dangerous section and the bolted connections on the motor train set were reasonably designed. Shao Wenbin [4] compared the permissible preload and the calculated maximum preloa to design the rational design of bolt connection in automotive suspension systems. These studies use theoretical calculations to verify the design reliability of the bolts by calculating the tensile strength of the bolt dangerous section, providing ideas for theoretical calculations for bolt connection design.

In addition, the finite element method also becomes a necessary supplement to the theoretical calculations. Cheng Fengwen [5] used ComosWork to make finite element simulation of internal pressure vessel bolt design and optimized bolt design. Xianzhen Huang [6] made reliability analysis of bolts with applied preload by using Abaqus, providing new ideas for the design of bolt connection. Zhang Chi [7] did finite element analysis (FEA) of bolts by LS-DYNA in order to find the tensile and yield limits of bolts at failure breakage by adding displacement to the bolts. It also improved method for easy breaking bolt of helicopter fuel tank These studies use FEA to investigate the bolt under load and to verify the soundness of the bolt connection design. This kind of approach is closer to real working conditions and provides a more convincing method to bolt design. It also provides an idea for the use of FEA for bolt design in this paper.

The design of bolt connection in the Mechanical Design Handbook mainly uses the hydrostatic principle to derive the forces on the bolts, while bolt connection in product design is more empirical. The theoretical design and finite element method studies show that most bolt connections are not designed with a combination of the two approach. Our research approach is to firstly design the bolt connection applied at the connection between the valve and the flanged pipe according to the relevant standards and bolt design guidelines. Secondly, the equivalent force on the bolt is calculated by using theoretical calculation (combined with the relevant formula) and the von-Mises stress on the bolt is calculated using finite element simulation software (ANSYS). Finally, the two results are compared. It was found that the results were generally consistent and met the design requirements. Thus, the reasonableness of the design will be proven.

This paper provides solutions for the design of bolted connections in valves based on comparing the results of theoretical design and FEA.

2. Design of Bolt Connection

2.1 Determination of The Number of Bolts, Nominal Diameter, and Arrangement in The Bolt Group

Taking the sea valve with a nominal diameter of 250mm as the object of study, the Chinese industry standard of flanged cast steel right angle sea valve "CB/T 3087-1994" was obtained by searching for the standards of the valve [8]. The provisions of the BS type flanged cast steel sea valve are as in Table 1. The flanged cast steel right-angle sea valve with a diameter of 250 mm requires 12 bolts of M16 on the flange to connect the pipe to the valve body. Twelve bolts are arranged in a circular pattern on the flange.

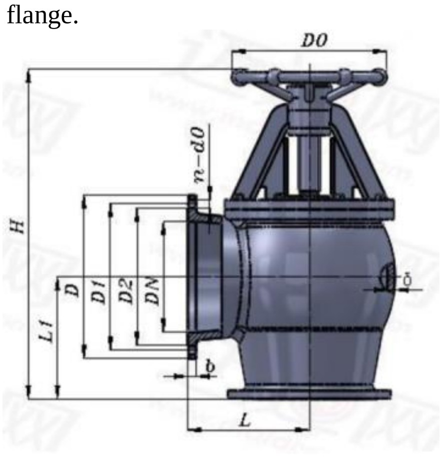

Fig. 2 - Diagram of valve body parameters

Table 1 - Dimensions relating to flanged cast steel sea valve

Through diameter	Structural dimensions（mm）			Flange size（mm）			Bolts（mm）	
(DN mm)	L	H	δ	D	b	d0	Th.	n
250	325	755	13.5	375	24	18	M16	12

Note: Th is the type of thread； n is the number of bolts.

2.2 Determining The Type of Bolt and Nut in A Bolt Set

On the valve body of the outlet valve, the set of bolts connecting the valve body to the flange at the end of the pipeline is used to resist axial forces to ensure the sealing of the valve body to the pipe connection. The bolts are connected through the through holes of the two flanges. As the length of the screw required is long and the axial force carried is large, the bolts are selected as semi-threaded bolts and the nuts must be tightened and reinforced. Based on the requirements for the connection, a general bolt connection can meet the requirements of this working condition, and the performance grade of the bolt and nut can be selected as Grade C（Grade C bolts are made of grades 4.6 or 4.8 steel, rolled from round steel, with a rough surface and not very precise dimensions). The details of properties of the selected grade can be found from Chinese national standard: GB/T 5780-2016 [9].

The gasket can increase the contact area, reduce the pressure, prevent loosening, and protect the bolt. As the machined surface cannot be perfect, the use of gaskets can fill the irregularities. Therefore, gaskets are used in this study.

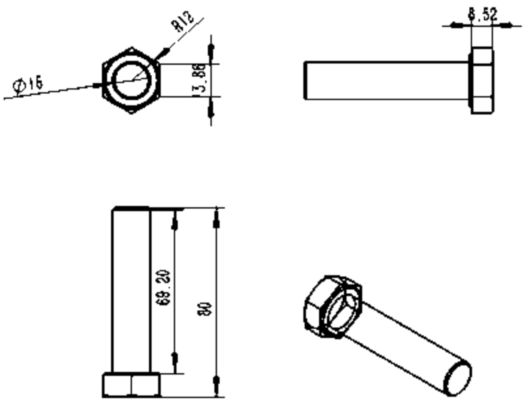

Fig. 3 - Diagram of bolt sizes

Once the type of bolt has been determined, the performance grade of the nut to be used with it needs to be selected. The design guideline is that when the bolt set is used in an overload condition, the bolt should break first without pullout of the bolt or nut. This is because the breakage of the bolt occurs suddenly, whereas the pullout of the thread occurs gradually. When matching nuts, as long as the performance grade of the nut is not less than 0.737 times the performance grade of the bolt, the bolt set will not have the pullout before the bolt breaks [10]. The Chinese national standard of grade C hexagonal nut GB/T 41-2016 [11] stipulates the performance grade of grade 5, which meets the requirements of selecting nuts.

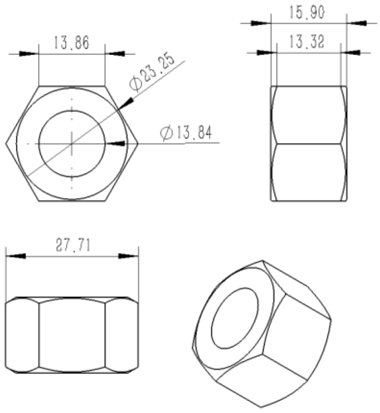

Fig. 4 - Diagram of nut sizes

2.3 Determining The Parameters of the Bolt and Nut

A coarse tooth thread, according to GB/T 95-2002 [12] are chosen. The flat washer with thickness of 3 mm, nut and bolt of 4.8 grade are selected. According to Guo-Xing et al., research on corrosion mechanism of materials related to offshore operations and the provisions of national standards, the bolt materials of Q235[13] are chosen. According to CB/T 3087-1994, the flange thickness of a sea outlet valve with a diameter of Φ250 mm is 22 mm and the connection is made with an integral steel pipe flange [14]. A thin gasket of 1 mm thickness is added between the pipe and the valve body. The thickness of the nut is 15 mm and the thickness of the flat gasket is 3 mm.

For common bolt connections, the formula for the length of thread allowance is:

$$a \approx (0.2 \sim 0.3)d \quad (1)$$

Note: a is the length of thread projection; d is the bolt diameter.

The bolt size chosen for this design is M16. The pre-determined length of the thread is calculated to be 4 mm. The overall thickness required is 69 mm and the bolt length is 70 mm according to national standards.

3. Methodology of FEA

3.1 Simplifying Models and Adding Materials

After the design has been completed, the valve body, bolts, nuts, flat gaskets, and pipework are modelled as 3D solids using SolidWorks software according to the criteria in the design (Fig. 5). The presence or absence of part of the valve of this combined model does not affect the FEA results as the model needs to be meshed first in ANSYS in order to carry out a FEA of the valve body structure. Before the analysis, the model can be simplified to reduce the computational time without affecting the results (Fig. 6). The body and cover material of the valve are cast steel——230-450.

Fig. 5 - Model of the valve

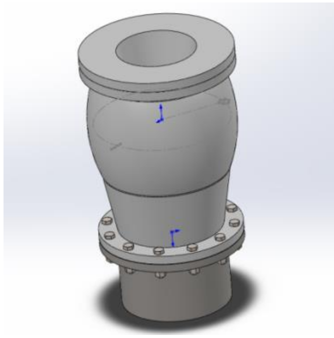

Fig. 6 - Simplified model of the valve

Table 2 - Valve body materials

Part name	Materials		
	Name	Brand	Standard number
Valve body	Cast steel	230-450	CB 772
Valve cover			

Table 3 - Parameters related to Fe360A and 230-450

Name of material	Modulus of elasticity (N/m^2)	Poisson's ratio	Mass density (kg/m^3)	Yield strength (N/m^2)
Fe360A	2.10E+11	0.274	7.83E+03	2.35E+08
230-450	2.11E+11	0.311	7.83E+03	2.48E+08

3.2 Mesh

The selection of the cell size is based on the accuracy of the calculation and the speed of the calculation. It is worth noting that higher number of mesh contributes to more accurate results. In present work, the tetrahedral mesh with a cell size of 5 mm is employed as shown in Fig. 7. The model was solved in ANSYS workbench, and the results were compared with the design calculations.

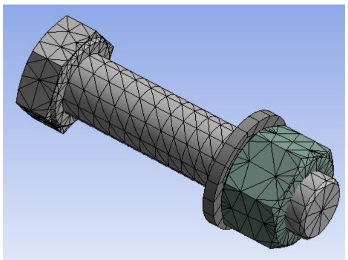

Fig. 7 - Image of the mesh on the bolt

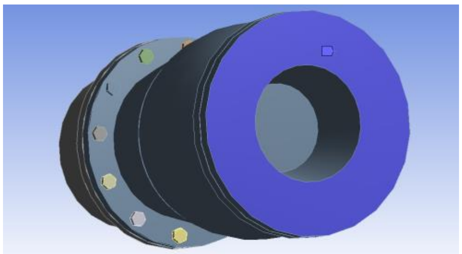

Fig. 8 - Fixed support

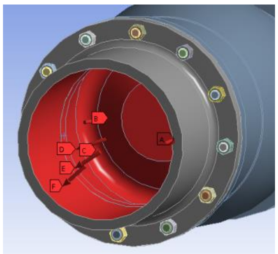

Fig. 9 - Internal mechanical boundary conditions

3.3 Boundary Conditions

Preload force formula is given by:

$$F_0 \leq (0.6 \sim 0.7)\sigma_s A_1 \qquad (2)$$

Taking the coefficient to the middle value of 0.65, the yield strength is known from the performance grade 4.8 is 320 MPa. The critical cross section of the bolt according to the formula for calculating the small diameter (d) of the external thread of the common metric thread is:

$$d = D - 1.0825P \qquad (3)$$

The smallest diameter of the M16 bolt was calculated to be 13.835 mm, with a maximum preload of 31,268 N.

Boundary conditions are applied to the valve body and fixed support are located on the valve cover surface. The fixed support is set as shown in Fig. 8. The bolt preload is set: load each bolt with the preload of 38241 N. The test pressure of 0.6 MPa was used to apply the normal load to each surface inside the valve body. The internal mechanical boundary conditions imposed on the valve body are shown in Fig. 8.

4. Results

4.1 Calculated Result

As the material chosen for the bolts is Fe360A, it is a elasto-plastic material that satisfying the fourth strength theory. It is believed that the density of distortion energy is the main cause of yielding. The deformation of a unit body taken from any point in a stressed object includes volume change and shape change, so the deformation energy of a unit body can be divided into volume change energy and shape change energy. The shape change energy per unit volume in a unit body is called the shape-changed strength ratio of the unit body **Error! Reference source not found.**. This is called the shape change energy. According to the fourth strength theory, the calculated stress in the preloaded state (σ_{ca}) is

$$\sigma_{ca} = \sqrt{\sigma^2 + 3\tau^2} \approx 1.3\sigma \qquad (4)$$

This formula considers the combination of tensile stress (σ) and torsional shear stress (τ), only the tensile strength needs to be calculated. The tensile strength of the dangerous section of the bolt is

$$\sigma_{ca} = \frac{1.3F_0}{\frac{\pi}{4}d_1^2} \qquad (5)$$

Notes.F_0 is the preload force, and d_1 is the small diameter of the bolt.

The preload force is 31,268 N and the small diameter of the bolt is 13.835 mm, thus it is calculated that $\sigma_{ca} \approx 270$ MPa.

4.2 FEA Result

The results of the analysis of the von-Mises stress on the bolt is shown in Fig. 9. The effect of not using the gasket on the bolt were also investigated, and the results showed that the von-Mises stress on the bolt without the gasket was higher. On the bolt, the maximum values of von-Mises stress occurred close to the middle section of the bolt, with values ranging from 265.97 MPa to 299.21 MPa, as shown in Fig. 11. The calculated value (of 270 MPa) is within the range indicated by the FEA results (265.97 MPa to 299.21 MPa) and this theoretical calculation is in general agreement with the results obtained from the FEA. The maximum and minimum principal stresses on the bolt set were also investigated. The results show that the maximum principal stress does not exceed the tensile strength and the minimum principal stress does not exceed the yield strength of the bolt.

5. Discussions and Conclusion

This study combines relevant references and guidelines for the design of bolt firstly to design the bolt connection of the valve body and pipe. The equivalent forces of the bolts in this condition are calculated using the equation of the fourth strength theory. The result was compared with the result of the FEA. It is found that the calculated value of bolt connection is consistent with the FEA value and they are smaller than the yield strength of the bolt. The bolt selected for this design has a performance grade of 4.8, which corresponds to a yield strength of 320 MPa. It is greater than the theoretically calculated equivalent stress value (270 MPa) and the von Mises stress value (from 265.97 MPa to 299.21 MPa) obtained from the FEA. This result indicates that the bolt will not yield under experimental conditions. The designed bolt meets the design requirements. It can prove that the design is reasonable.

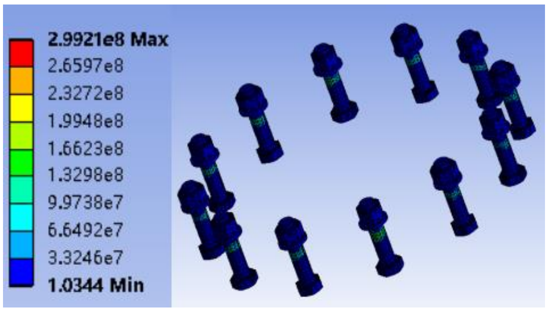

Fig. 9 - Distribution of equivalent forces

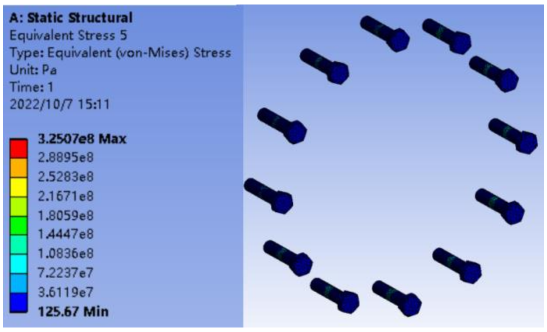

Fig. 10 - Distribution of equivalent forces (no gasket)

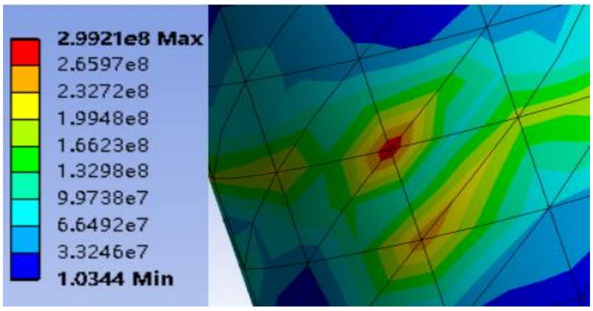

Fig. 11 - Equivalent force values

Fig. 12 - Distribution of maximum principal stress

Fig. 13 - Distribution of minimum principal stress

This study has been compared with other studies in this area. For example, Li Chang [3] used the fourth strength theory to calculate the equivalent force of the bolt on the high speed train and to calculate the tensile strength of the dangerous section of the bolt. He used theoretical calculation to verify the reliability of the bolt design. The theoretical calculation in this study is consistent with the method used by Li Chang [3]. However, this study also used FEA to verify the reliability. Another scholar, Zhang Chi [7] used ANSYS to do FEA of the bolt and found the tensile limit and yield limit of the bolt at failure. However, he does not have the theoretical calculation part.

This study is based on the relevant requirements of bolt design and realizes the design of bolts at the connection between BS-type flange cast steel right-angle sea valve and flange pipeline. On the basis of the same theoretical calculation as other scholars, the reliability of bolt connection is verified by FEA method, which improves the reliability of bolt connection.

There are some limitations in the research process. For example, firstly, the element size of the mesh was 5 mm. The results of the FEA could reflect the result to a large extent. However, the computer used did not have enough RAM to allow for further reduction of the element size. Secondly, fatigue loading on the bolts is not considered in this study. However, the references that have been reviewed do not include fatigue verification of bolt designs either. Moreover, due to our own conditions, we did not have access to the opening and closing conditions of the valve under the working condition. So, it is unable to derive a reasonable alternating load for the simulation. Thirdly, under this working condition, because the bolt connection between the valve and the pipeline mainly bears axial force, only the effect of axial force is considered in the design of the bolt set. If the bolts are used in other situations, such as fan anchor bolts and fan blade bolts, the influence of overturning moment and transverse force should be considered in the design. In addition, finite element results are not only limited to the von Mises stress, but also to consider the impact of the principal stresses of maximum, intermediate and the minimum stress.

In view of the above problems, the influence of fatigue can be fully considered when verifying the reliability of the design. Finally, this paper can be a reference to verify the reliability of bolt design (by combining theoretical calculation and FEA results).

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