Research on Engineering Calculation of Bolt in Wind Turbine Cylinder Flange

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Abstract：High-strength bolts are the most commonly used components in wind turbines and play a decisive role in the overall performance of wind turbines. They are widely used due to their advantages of large load bearing, good stress performance and fatigue resistance. Combining VDI2230, mechanical calculation and simulation analysis, a calculation method of bolt connection strength of wind turbine generator system was proposed. Firstly, the load of the root of the wind turbine generator tower was decomposed into six basic loads. The six loads can be converted into single bolt axial load and transverse load. Then, calculate and analysis the pre-tightening force, load analysis, stress of key bolt based on VDI2230. The comparison between the theoretical calculation results and the finite element simulation results shows that the deviation between the two is 2.5%, which can verifies the accuracy of the calculation method. This high-efficiency and high-precision calculation method for the bolt is also useful for other equipment.

Keyword: Bolted connection; VDI2230; Load calculation; Finite element analyze; Wind turbine generator system

1 Introduction

Bolt connection has the characteristics of high connection rigidity, easy operation and easy to disassemble, which is the most widely used mechanical connection mode. Bolt connection is the main way of connection in aerospace equipment such as aircraft engine and launch vehicle, energy equipment such as wind turbine generator system and nuclear power unit and transportation equipment such as automobiles and high-speed rail. The reliability of bolt connection structure is one of the key factors to ensure reliable work of equipment.

Bolt connections involve almost all parts of the wind turbine generator system. In the case of wind turbine generator system, connections between the tower drums, tower drums and yaw bearing, front rack and rear frame and variable oar bearings and vane are all done through the flange bolts. Therefore, the selection of bolts and strength checking is an important guarantee for the reliability of the wind turbine generator system. With the leap-forward development of wind turbine generator system in China, the installed power is getting higher and higher and the service load is becoming worse and worse. How to guarantee the reliability of wind turbine generator system becomes an important problem. As an important part of wind turbine generator system, bolt has become one of the main difficulties in reducing cost of wind turbine generator system due to the uncertainty of various aspects.

Recently, with the development of wind turbine generator system to the megawatt level, the power of the unit has been increasing, the cone tower has taken the leading position, and the shape of it has been increasing. The megawatt-level wind turbine generator system is typically more than 60 meters high. As a kind of high-rise structure, the influence of wind load should be mainly considered in the structural design. The quality of the generator, hub and vane on the top of the tower is generally larger. So the tower is not just bear the dynamic load produced by the rotation of the vane, also be affected by wind loads. In recent years, there have been many accidents in wind turbine generator system collapse. Later identification and analysis indicated that the cause of the accident was not only the heavy load

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caused by the strong wind, but also the insufficient strength of the flange connecting bolts and the improper fastening of the high strength bolts.

At present, there are mainly finite element analysis [1-3] and scientific calculation [4-6] two ways to analyze and check of bolt connection strength. In the process of analysis in the finite element analyze software, preload can be loaded by direct loading method, equal effect method, effective strain method and equivalent temperature method. For example, the Bolt Pretension command in ANSYS Workbench can be used to apply bolt pretension directly. But these loading methods, or can't pass shear stress, or cannot simulate reality bolt and the friction behavior between bolt and connected part, and cannot consider pretension loss from the nut loosening. This leads to the large bolt stress in the finite element simulation. At the same time, the number of bolts in wind turbine generator system is large and the load is complex. This results in a large calculation of finite element analysis and a long calculation time. Therefore, the finite element calculation is generally not used as the method for checking bolt structure in wind turbine generator system.

At present, VDI2230 is used in wind turbine generator system industry to analyze and calculate the bolt connection strength of wind turbine generator system. This method has been used in engineering practice for over 30 years and is widely recognized and cited. In this paper, based on the known parameters of bolt fastening and load condition of flange, the most dangerous bolts were found by means of computation of transverse load and axial loads of every bolt. Then, VDI2230 was used to check the most dangerous bolt. At the same time, ANSYS workbench was used to simulate the bolted structure. Finally, the reliability of VDI2230 calculation is verified by comparing the calculation results with the simulation structure.

2 Load Equivalent Method

The load of the flange is decomposed into six basic loads, as shown in Fig. 1, respectively, F_x, F_y, F_z, M_x, M_y and M_z. Since the VDI2230 is calculated for a single bolt, it is necessary to assign the flange load to every bolt before the formal calculation.

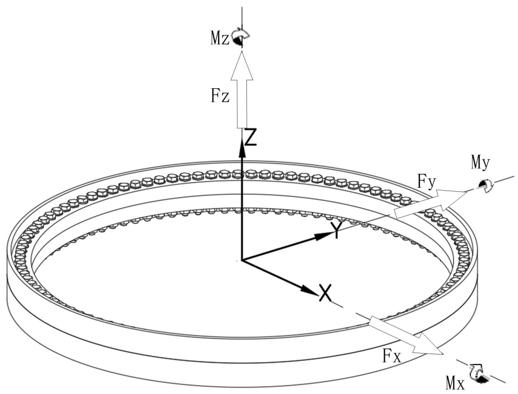

Fig. 1. The bolt connection structure of tower drum

2.1 Basic Load Handling Methods

F_x and F_y can be evenly assign to each bolt as transverse loads. The component forces of each bolt are $F_{xi}(i=1,2,\cdots,n)$ and $F_{yi}(i=1,2,\cdots,n)$, as shown in Fig.2-b and Fig.2-c, they are the same size and direction. M_z can be evenly assigned to each bolt as transverse loads. The component forces of each bolt are $F_{zi}(i=1,2,\cdots,n)$, as shown in Fig.2-a, they are the same size but different direction. In this way, the transverse load on each bolt is $F_{xi}+F_{yi}+F_{zi}$.

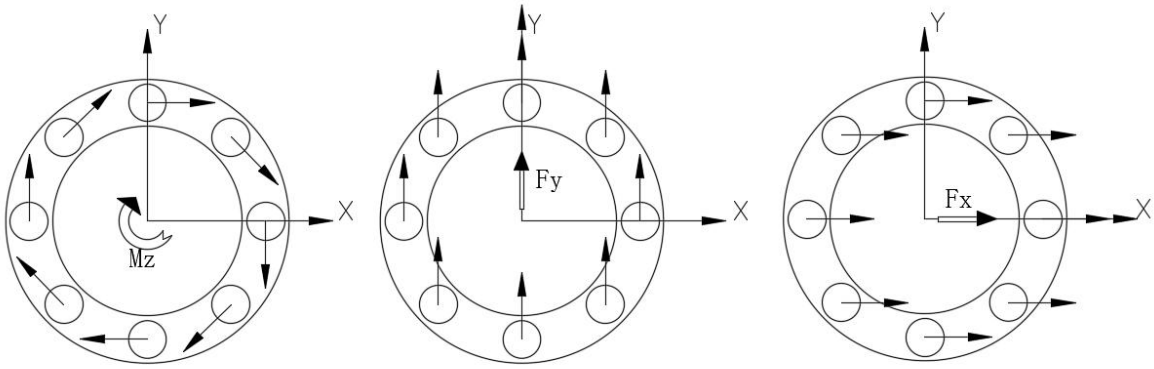

Fig. 2. The transverse load of bolts on flange circumferences for various conditions

F_z can be evenly assigned to each bolt as axial load. The component forces of each bolt are $F'_{zi}(i=1,2,\cdots,n)$, as shown in Figure 3-a, they are the same size and direction. M_x and M_y can be evenly assigned to each bolt as axial loads. The component forces of each bolt are $F'_{xi}(i=1,2,\cdots,n)$ and $F'_{yi}(i=1,2,\cdots,n)$. Their size and direction are all different. The farther away the bolt is from the axis, the greater the axial force is. Their directions are shown in Figure 3-b and Figure.3-c.

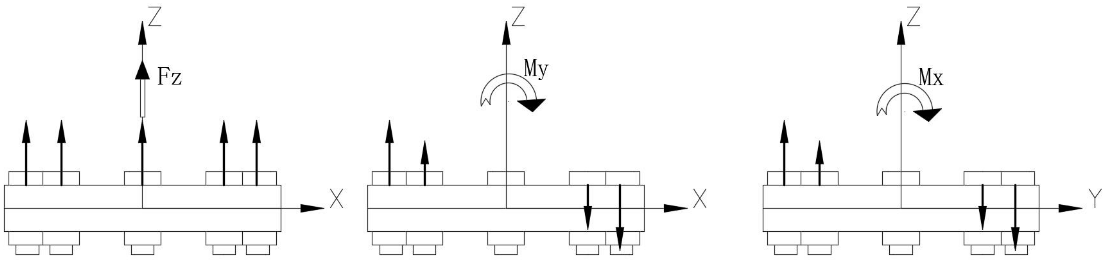

Fig. 3. The axial load of bolts on flange circumferences for various conditions

2.2 Load Calculation Method

First, calculate the transverse load of every bolt. Component force of F_x in every bolt is $F_{xi}=F_x/n$, component force of F_y in every bolt is $F_{yi}=F_y/n$. Component force of M_z in every bolt is $F_{zi}=M_z/(n*R)$. Further decompose it along X and Y directions as F_{zx} and F_{zy} as Fig.4. The calculation method of transverse load for every bolt is shown in Equation (1) and Equation (2).

$$F_i^{trans}=\sqrt{(F_{xi}+F_{zi}*\cos i\theta)^2+(F_{yi}+F_{zi}*\sin i\theta)^2} \quad (1)$$

$$\theta=\frac{2\pi}{n}(\text{n is the number of bolt}，i=(1,2,\cdots n)) \quad (2)$$

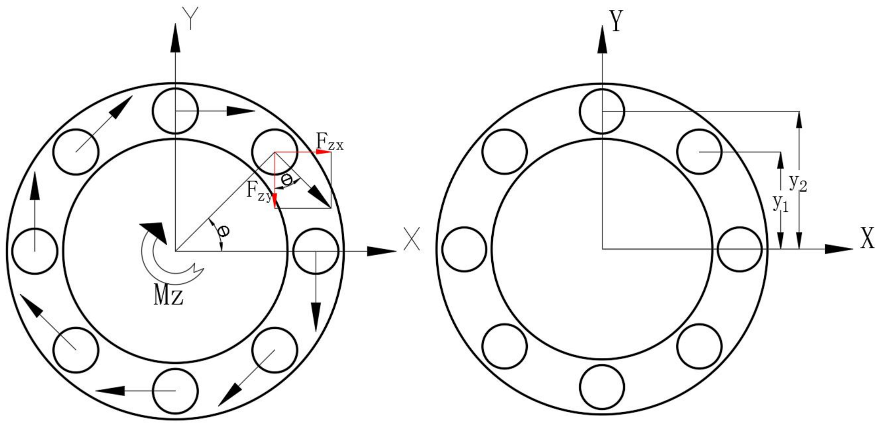

Fig. 4. The load calculation diagram

Second, calculate the axial load of every bolt. Component force of F_z in every bolt is $F'_{zi} = F_z / n$. Component force of M_x and M_y in every bolt can be calculated according to Equation (3).

$$F'_{xi} = \frac{M_x \cdot y_i}{\sum_{j=1}^{n} y_j^2}; F'_{yi} = \frac{M_y \cdot x_i}{\sum_{j=1}^{n} x_j^2}; \tag{3}$$

The calculation method of axial load for every bolt is shown in Equation (4).

$$F_i^{axial} = F'_{xi} + F'_{yi} + F'_{zi} = \frac{M_x \cdot y_i}{\sum_{j=1}^{n} y_j^2} + \frac{M_y \cdot x_i}{\sum_{j=1}^{n} x_j^2} + \frac{F_z}{n} \tag{4}$$

Where, F_i^{axial} represents the axial load of the bolt numbered '*i*', F'_{xi} is the component force of M_x in bolt numbered '*i*', F'_{yi} is the component force of M_y in bolt numbered '*i*', y_i is the distance between *X* axis and the bolt numbered '*i*', x_i is the distance between *Y* axis and the bolt numbered '*i*'.

3 Checking Calculation

3.1 Determine the Minimum Clamping Force Required F_{Kerf}

a) The Frictional Force Passing the Transverse Load on the Interface

$$F_{KQ} = \frac{F_{Q\max}}{q_F \cdot \mu_T} \tag{5}$$

F_{Qmax} is transverse load, q_F is the number of interface and μ_T is friction coefficient at the interface.

b) Sealing Medium

There is no seal pressure problem, this one is not considered.

c) To Prevent Open

The previous load equivalent process converts the whole load into the concentric load and eccentric clamping of the bolt, at the same time, there is no seal pressure problem.

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$$F_{KY} + F_{KA} = 0 \tag{6}$$

$$F_{Kerf} \geq \{\max(F_{KQ}; F_{KY} + F_{KA})\} = F_{KQ} \tag{7}$$

F_{KQ} is minimum clamp load for transmitting a transverse load and/or a torque by friction grip, F_{KA} is minimum clamp load at the opening limit, F_{KP} is minimum clamp load for ensuring a sealing function.

3.2 Distribution of Work Load, Elastic Compliance and Load Conductivity

a. Elastic Compliance of Clamped Part

Take the auxiliary dimension value.

$$D_A = (\frac{2\pi PCD}{N_{blot}} - d_h + b_{fl})/2 \tag{8}$$

Because there is not much difference between the basic section and the cut surface, it can be considered that D_A is equal to D_A'. The *PCD* is the pitch diameter of the bolt center. The d_h is the bolt hole diameter. The b_{fl} is flange width. N_{blot} is the number of bolt.

$$\beta_L = l_k / d_{wa}, y = D_A' / d_{wa} \tag{9}$$

If the bolt connection mode is DSV, the calculation formula to alternate deformation cone angle is as follows.

$$\tan\varphi_D = 0.362 + 0.032\ln(\beta_L/2) + 0.153\ln y \tag{10}$$

If the bolt connection mode is DSV, joint coefficient for the type of bolted joint is $w=1$, and if it is ESV, $w=2$ .if the interface area differs from the circular form, an average diameter is to be used as:

$$D_{A,Gr} = d_{wa} + w \cdot l_k \cdot \tan\varphi_D \tag{11}$$

If $D_{A,Gr}$ is greater than D_A, Equation (12) should be used (E_p is the elastic modulus of the connected part) to calculate elastic resilience of concentrically clamped parts δ_P^Z.

$$\delta_P^Z = \frac{\frac{2}{w \cdot d_h \cdot \tan\varphi_D} \ln\left[\frac{(d_{wa} + d_h)(D_A - d_h)}{(d_{wa} - d_h)(D_A + d_h)}\right] + \frac{4}{D_A^2 - d_h^2}\left[l_K - \frac{(D_A - d_{wa})}{w \cdot \tan\varphi_D}\right]}{E_p \cdot \pi} \tag{12}$$

b. Elastic Compliance of Bolt

The bolt connection is substitute into Equation (13).

$$\delta_S = \delta_{SK} + \delta_1 + \delta_{Gew} + \delta_{GM} = \frac{4}{\pi \cdot E_S} \cdot \left(\frac{0.5 \cdot d}{d^2} + \frac{l_1}{d_T^2} + \frac{l_{Gew} + 0.5d}{d_3^2} + \frac{0.4d}{d^2}\right) \tag{13}$$

l_1、l_{Gew}、d_T、d_3、d are as shown in Figure 5, δ_1 is elastic resilience of section l_1 , δ_{SK} is elastic resilience of the bolt head, δ_{Gew} is elastic resilience of the unengaged loaded thread, δ_{GM} is elastic resilience of the engaged thread and of the nut or tapped thread region,(E_s is the elastic modulus of the bolt).

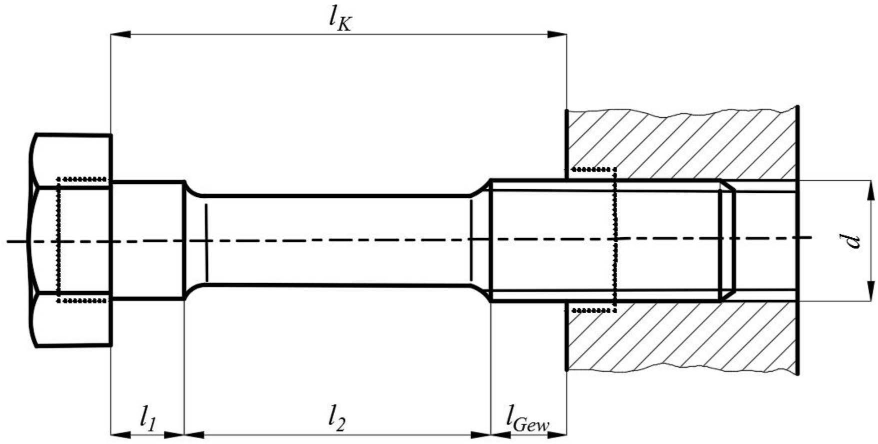

Fig. 5. The bolt size chart

When consider the elastic deformation of the eccentricity clamped part.

The eccentricity distance is:

$$s_{sym} = \frac{c_T}{2} - e \tag{14}$$

The length of the deformation cone is:

$$l_V = \frac{D_A - d_{wa}}{2 \cdot \tan \varphi_D} \tag{15}$$

The rotation equivalent moment of the deformation cone is:

$$I_{Bers}^{V} = 0.147 \cdot \frac{\left(D_A - d_{wa}\right) \cdot d_{wa}^3 \cdot D_A^3}{D_A^3 - d_{wa}^3} \tag{16}$$

$$I_{Bers}^{Ve} = I_{Bers}^{V} + s_{sym}^2 \cdot \frac{\pi}{4} D_A^2 \tag{17}$$

The rotation equivalent moment of the deformation cone is:

$$I_{Bers} = \frac{l_K}{\frac{2}{w}\left(l_V / I_{Bers}^{Ve}\right)} \tag{18}$$

The flextural resilience is:

$$\beta_P^Z \approx \frac{l_K}{E_P \cdot I_{Bers}} \tag{19}$$

Synthesize the above formula, the elastic deformation of the eccentricity clamped part can be calculated as:

$$\delta_P^* = \delta_P^Z + s_{sym}^2 \cdot \beta_P^Z \tag{20}$$

c. Load Conductivity *n*

The connection model of bolt connection can be selected through Table 1 in VDI2230 and Figure 3.

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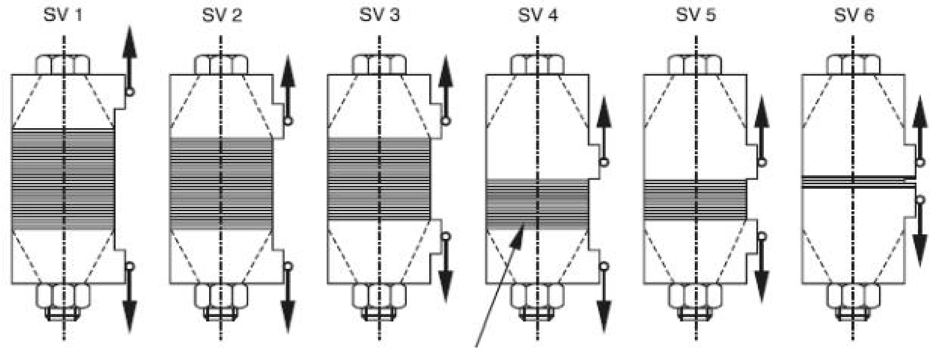

Fig. 6. Joint types according to type of load introduction

Dimensional proportions are a_k/h and l_A/h. The load conduction coefficient is obtained in Table 5.2/1 by interpolation method. Then the load coefficient can be calculated according to Equation (21).

$$\Phi_n^* = n \cdot \frac{\delta_p^Z}{\delta_S + \delta_p^*} \tag{21}$$

For the bolt additional force, according to Equation (22), in the case of no release, the axial maximum increase of the bolt load can be calculated as:

$$F_{SA\max} = \Phi_n^* \cdot F_{A\max} \tag{22}$$

For unstressed plates, there is a maximum reduction in additional load.

$$F_{PA\max} = \left(1 - \Phi_n^*\right) \cdot F_{A\max} \tag{23}$$

3.3 Change of Preload

Select coefficients according to VDI2230. In consideration of the tension load (not considering the lateral load on the symmetric side), the exact value f can be selected in VDI2230 based on the surface roughness of the parts. If the exact roughness value cannot be obtained, the default value can be selected. If $R_Z \leq 16\mu m$, values can be obtained. The preload loss caused by embedding relaxation can be calculated as:

$$F_Z = \frac{f}{\left(\delta_S + \delta_P^*\right)} \tag{24}$$

3.4 Installation Preload Calculation of Bolts.

The temperature difference in China's wind power region is not large, so the change in the preload as a result of a temperature different from room temperature is $\Delta F_{Vth}^{'} = 0$.

The installation preload can be calculated according to Equation (26),the assembly preload is:

$$F_M = F_{Kerf} + F_{PA\max} + F_Z + \Delta F_{Vth}^{'} \tag{25}$$

3.5 Checking of Bolt Stress

When the bolt bears the working load, the maximum axial force of the bolt can be calculated according to Equation (26)

$$F_{Smax} = F_{M\max} + \Phi_n^* \cdot F_{A\max} - \Delta F_{Vth}' \quad (26)$$

Calculation of maximum axial tensile stress

$$\sigma_{Z\max} = F_{Smax} / A_0 \quad (27)$$

Calculation of maximum shear stress

$$\tau_{\max} = \frac{F_{M\max} \cdot \frac{d_2}{2}\left(\frac{P}{\pi \cdot d_2} + 1.155\mu_{G\min}\right)}{\frac{\pi \cdot d_0^3}{16}} \quad (28)$$

$$\sigma_{red.B} = \sqrt{\sigma_{Z\max}^2 + 3(k_\tau \cdot \tau_{\max})^2}\,(k_\tau = 0.5) \quad (29)$$

3.6 Calculation Case

Took the data of wind turbine generator system from Taiyuan Heavy as an example. The bolt grade is 10.9, size specification is M56×320 and diameter of the hole is 59 mm. The elastic modulus of bolts is 2.06E5MPa, elastic modulus of flange is 2.06E5 MPa and thread friction factor is 0.1(Dacro lubrication). The number of bolts is 104, flange width is 200 mm and PCD is 1845 mm. The extreme load is shown in the Table 1. The equivalent maximum stress of bolts calculated according to the above data is 637.55 MPa.

Table 1. The load of tower drum root

Sharing part of the load	Value
Fx	318.2kN
Fy	8.01kN
Fz	-4596.6kN
Mx	2383.6kN·m
My	75030kN·m
Mz	-6457.4kN·m

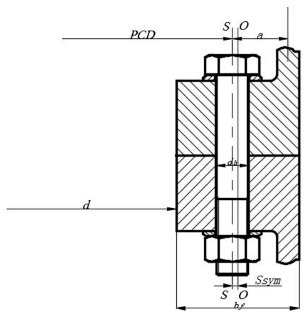

Fig. 6. Parameters for determining the load introduction factor

4 Comparison between the results of VDI2230 and finite element analysis

4.1 Finite Element Model

A finite element model of connection structure is established in Hypermesh. The model is divided by

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652288 hexahedral grids. The model includes upper flange and lower flange and 104 bolts and nuts. Bolt elastic modulus is 2.06E5 MPa, Poisson's ratio is 0.3 and density is 7850.

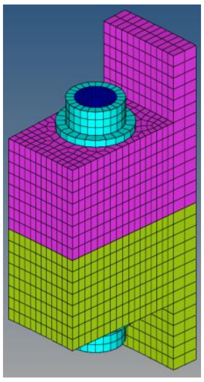


Fig. 7. A part of bolt connection's mesh

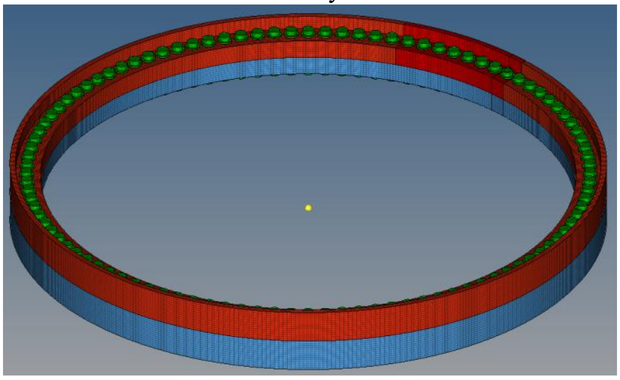


Fig. 8. The overall mesh

4.2 Boundary Condition

Impose a fixed constraint on the lower flange circumference. Impose forces on top flange, F_x=318.2kN, F_y=8.01kN, F_z=-4596.6kN. Impose torque on the contact surface between upper flange and the lower flange, M_x=2383.6kN·m, M_y=75030kN·m, M_z=-6457.4kN·m. And the bolt preload is 1185kN.

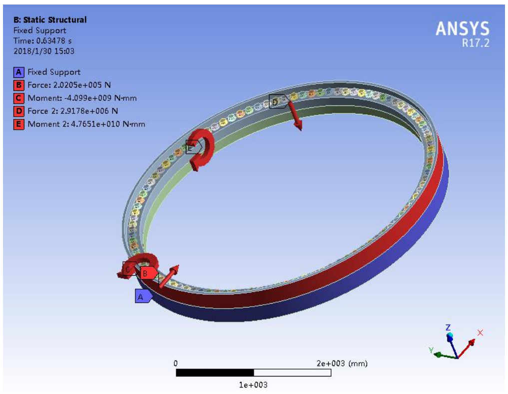
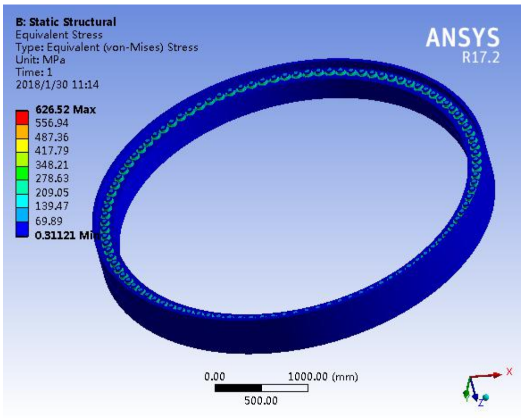


Fig. 9. The boundary condition of simulation

4.3 Analysis Result

The stress value of every component is under the yield strength after the bolt applied bolt preload. After applying the extreme condition, contact surfaces are still in good contact, and the stress value increases slightly. Fig.11 shows the stress nephogram after applying bolt preload, and the maximum value of stress is 626.52MPa. Fig.12 shows the stress nephogram after applying extreme load. The maximum value of stress is 653.95 MPa, increasing slightly. The results were 2.5% higher than the calculated results.



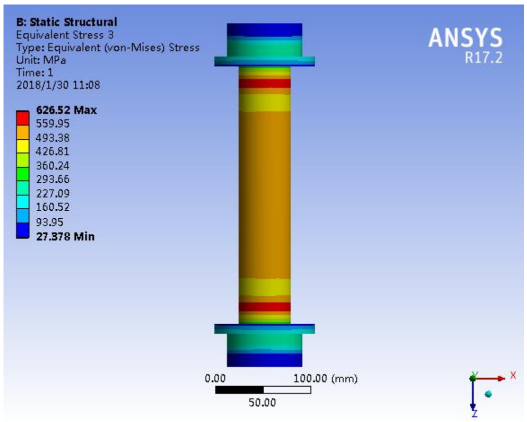
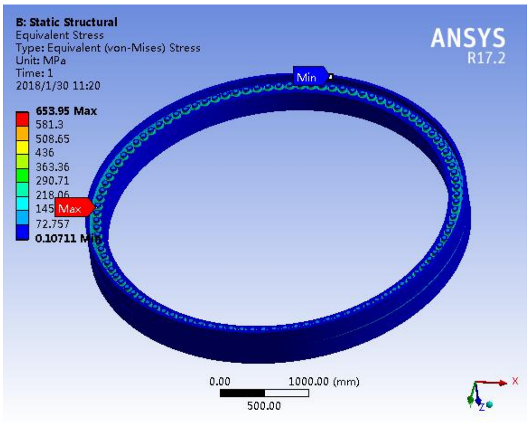


Fig. 10. The overall equivalent stress before preload applied

Fig. 11. The bolt equivalent stress before preload applied



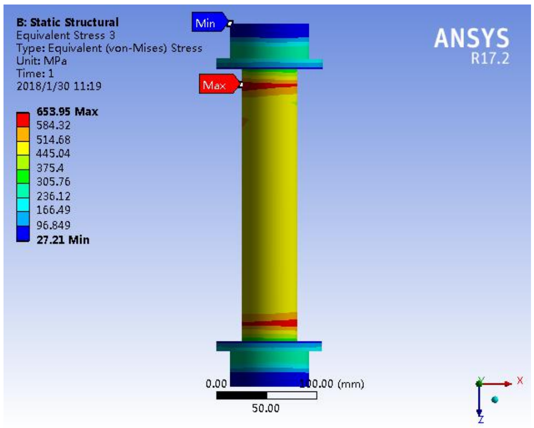


Fig. 12. The overall equivalent stress after preload applied

Fig. 13. The bolt equivalent stress after preload applied

5 Conclusion

By combining the mechanical analysis with VDI2230, a set of calculation method for connecting bolt of tower cylinder flange was obtained. The following conclusions were mainly drawn:

1）A load conversion method is provided, which can obtain the load condition of single bolts through six basic loads, it can be conveniently used to calculate the load of the flange circumferential bolt.

2）Take the bolt connection at the bottom of the tower drum as an example for calculation and FEM analysis. Using the known structure parameters of the tower bolt connection and the flange load. Calculate the maximum stress on the bolt according to the selected calculation procedure and compare it to the results of the simulation analysis, As a result, it was found that the simulation result was 2.5% larger than the calculation result, indicating that the equivalent method of the load and the bolt calculation method were accurate.

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