# Engineering Calculation and Simulation Analysis Method of Bolt Connections Based on VDI2230

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**Abstract:** Bolt connection is one of the most important connection methods in wind turbine. The safety design and checking of bolt connection structure is the key to ensure the reliable operation of wind turbine. VDI2230 is a widely used method for bolt calculation. In this paper, the flange bolt connection at yaw bearing is calculated based on VDI2230, and the calculated results such as elastic flexibility of bolt, elastic flexibility of connecting piece and peeling force of internal thread are simulated and analyzed. The accuracy of VDI2230 is further verified by comparing the result of simulation analysis and the result of VDI2230 calculation. Result analysis found that the error of simulation analysis and VDI2230 calculation is less than 2%. It has reference significance for high-efficiency and high-precision calculation method for bolt strength.

**Key words:** **S**imulation; VDI2230; Bolt; Thread stripping; Wind turbine

## 1 Introduction

Bolt connection has the characteristics of high connection rigidity, easy operation and easy disassembly. It is the most widely used mechanical connection mode. The bolt connection involves almost all parts of wind turbine. Taking wind turbine generators as an example. The important connections between the tower drums, tower drums and yaw bearing, front frame and rear frame, variable propeller bearing and blade are realized by flange bolt. Therefore, the selection of bolts and strength check are important guarantee of wind turbine reliability. Recently, with the development of wind turbine to MW class, the power of wind turbine is increasing, the service load is getting worse and worse, and the quality of wind turbine is becoming an important problem to every wind turbine enterprise. In recent years, wind power industry has had many accidents of tower drums tube collapsing. After appraisal and analysis, it is found that in addition to the excessive load caused by strong wind, most of them are accompanied by insufficient strength of flange connecting bolts in tower drums, problems with improper fastening of high-strength bolts during installation and construction and so on. Bolts as an important part of wind turbine equipment, due to the uncertainty of its various characteristics, has become one of the main difficulties in reducing the cost of wind turbine design.

At present, VDI2230 is widely used in wind turbine bolt connection strength analysis in wind power industry. This method has been used in engineering practice for more than 30 years, and has been widely accepted and cited. At this stage, the analysis of bolt connection is mainly focused on the stiffness and strength of bolt connection. The reciprocal of stiffness is flexibility. In order to determine the load of screw joint correctly, the flexibility of screw joint must be calculated. Scientists all over the world have done a lot of research [1-2] and put forward their formulas for calculating flexibility. For the simulation analysis of the stiffness of single bolt connection, the 2D model is used to analyze the stiffness of single bolt connection [3-6]. But that method is only used for axis symmetric model, and for the stiffness simulation of bolt connections in flange connections, it is not possible to do simulations. Martínez-Martínez M et al also conducted simulations and experiments on internal thread stripping, all of which are based on 2D analysis, the effect of spiral angle on screw thread is not taken into account. In this paper, the equivalent 3D simulation analysis of multi-bolt flange connection of yaw bearing outer ring is carried out, and an accurate model of bolt and internal thread is established for simulation

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analysis. Because of the finer finite element method, the simulation results can be compared with the results of VDI2230 calculation, and verify the VDI223 0 accuracy. Bolt connection described as ESV in VDI2230, which is, screw connection. In the actual failure it is possible to have screw peeling and screw breaking. In this paper the screw connection is calculated according to VDI2230 and the failure sequence of screw connection at the yaw bearing is analyzed by simulation.

## 2 Calculation

### 2.1 Determine the Minimum Clamping Force Required $F_{Kerf}$

a) 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.

$$F_{KP} + F_{KA} = 0 \tag{1}$$

$F_{KA}$ is minimum clamp load at the opening limit, $F_{KP}$ is minimum clamp load for ensuring a sealing function.

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

When transverse load applied，in order to prevent the connector from sliding laterally，a clamp load must be applied in axis as

$$F_{KQ} = \frac{F_{Q\max}}{q_F \cdot \mu_T} \tag{2}$$

$F_{KQ}$ is minimum clamp load for transmitting a transverse load, $F_{Qmax}$ is transverse load, $q_F$ is the number of interface and $\mu_T$ is friction coefficient at the interface.

$$F_{Kerf} \geq \{\max(F_{KQ}; F_{KP} + F_{KA})\} = F_{KQ} \tag{3}$$

### 2.2 Distribution of Work Load, Elastic Compliance and Load Conductivity

a. Elastic Compliance of Bolt

The bolt connection is substitute into Equation (4).

$$\delta_S = \delta_{SK} + \delta_1 + \delta_{Gew} + \delta_{GM} = \frac{4}{\pi \cdot E_S} \cdot \left( \frac{l_1}{d_T^2} + \frac{l_{Gew} + 0.5d \cdot 2}{d_3^2} + \frac{0.4d + 0.33d}{d^2} \right) \tag{4}$$

$l_1$、$l_{Gew}$、$d_T$、$d_3$、$d$ are as shown in Figure 1， $\delta_1$ is elastic resilience of section $l_1$, $\delta_{SK}$ is elastic resilience of the bolt head, $\delta_{Gew}$ is elastic resilience of the unengaged loaded thread, $\delta_{GM}$ is elastic resilience of the engaged thread and of the nut or tapped thread region, ($E_s$ is the elastic modulus of the bolt).

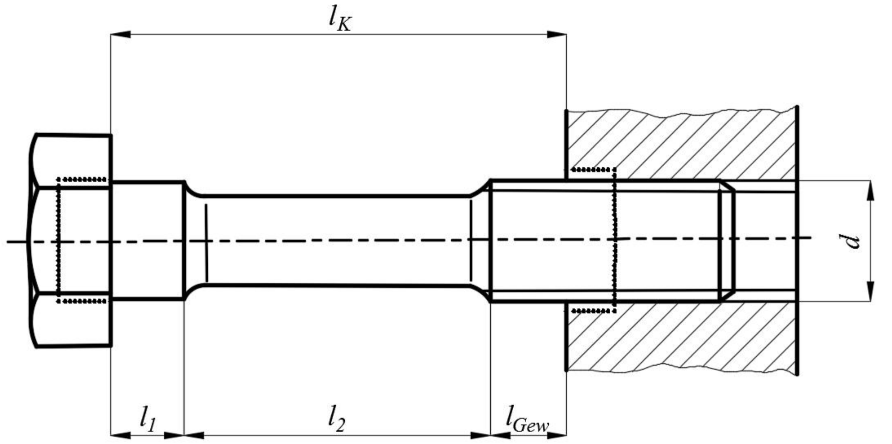


**Fig. 1.** The bolt size chart

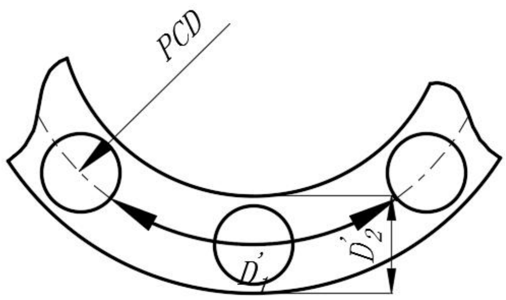


**Fig. 2.** Parameters for determining the auxiliary dimension

b. Elastic Compliance of Clamped Part

Take the auxiliary dimension value.

$$D_A = \frac{D_1^{'} + D_2^{'}}{2} = (\frac{2\pi PCD}{N_{blot}} - d_h + b_{fl}) / 2 \tag{5}$$

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, $D_1^{'}$ and $D_2^{'}$ are as shown in Figure 2.

Length ratio $\beta_L$ can be calculated as:

$$\beta_L = l_k / d_{wa}, y = D_A^{'} / d_{wa} \tag{6}$$

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

$$\tan\varphi_D = 0.348 + 0.013 \ln \beta_L + 0.193 \ln y \tag{7}$$

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:

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$$D_{A,Gr} = d_{wa} + w \cdot l_k \cdot \tan\varphi_D \tag{8}$$

If $D_{A,Gr}$ is greater than $D_A$, Equation (9) should be used ($E_p$ is the elastic modulus of the connected part) to calculate elastic resilience of concentrically clamped parts $\delta_P^Z$.

$$\delta_P^Z = \frac{\frac{2}{w \cdot d_h \cdot \tan\varphi_D} \ln\left[\frac{(d_{wa}+d_h)(D_A-d_h)}{(d_{wa}-d_h)(D_A+d_h)}\right] + \frac{4}{D_A^2-d_h^2}\left[l_K - \frac{(D_A-d_{wa})}{w \cdot \tan\varphi_D}\right]}{E_p \cdot \pi} \tag{9}$$

When consider the elastic deformation of the eccentricity clamped part.

The rotation equivalent moment of the deformation cone is:

$$I_{Bers}^{Ve} = 0.147 \cdot \frac{(D_A - d_{wa}) \cdot d_{wa}^3 \cdot D_A^3}{D_A^3 - d_{wa}^3} + s_{sym}^2 \cdot \frac{\pi}{4} D_A^2 \tag{10}$$

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

$$\delta_P^* = \delta_P^Z + \left(\frac{c_T}{2} - e\right)^2 \cdot \frac{\tan\varphi_D}{E_P \cdot w \cdot I_{Bers}^{Ve} \cdot (D_A - d_{wa})} \tag{11}$$

c. Load Conductivity $n$

The connection model of bolt connection can be selected through Table 5.21 in VDI2230 and Figure 3.

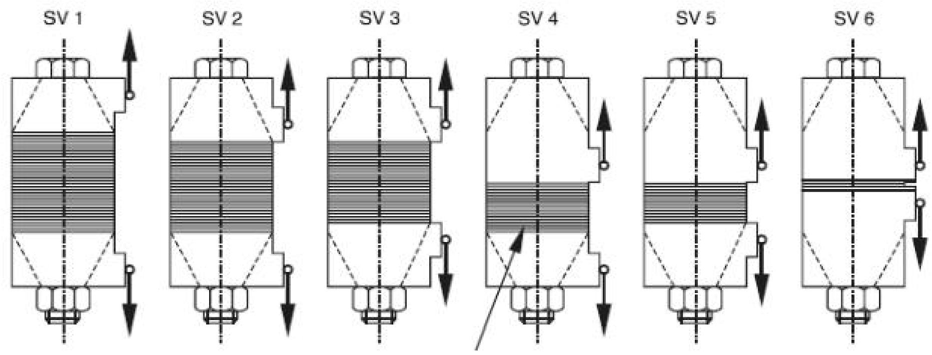


**Fig. 3.** Joint types according to type of load introduction

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 (12).

$$\Phi_n^* = n \cdot \frac{\delta_p^Z}{\delta_S + \delta_p^*} \tag{12}$$

For the bolt additional force, according to Equation (13), in the case of no release, the axial maximum increase of the bolt load can be calculated as:

$$F_{SA\max} = \Phi_n^* \cdot F_{A\max} \tag{13}$$

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

$$F_{PA\max} = \left(1-\Phi_n^*\right)\cdot F_{A\max} \tag{14}$$

### 2.3 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 $R_Z \le 16\mu m$ , values can be obtained. The preload loss caused by embedding relaxation can be calculated as:

$$F_Z = \frac{f}{\left(\delta_S + \delta_P^*\right)} \tag{15}$$

### 2.4 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 (16), the assembly preload is:

$$F_M = F_{Kerf} + F_{PA\max} + F_Z + \Delta F_{Vth}^{'} \tag{16}$$

### 2.5 Checking of Bolt Stress

When the bolt bears the working load, the maximum axial force of the bolt can be calculated according to Equation (17)

$$F_{Smax}{=}F_{M\max} + \Phi_n^* \cdot F_{A\max} - \Delta F_{Vth}{'} \tag{17}$$

Calculation of maximum axial tensile stress

$$\sigma_{Z\max} = F_{Smax} / A_0 \tag{18}$$

Calculation of maximum shear stress

$$\tau_{\max} = \frac{F_{M\max} \cdot \dfrac{d_2}{2}\left(\dfrac{P}{\pi \cdot d_2} + 1.155\mu_{G\min}\right)}{\dfrac{\pi \cdot d_0^3}{16}} \tag{19}$$

$$\sigma_{red.B} = \sqrt{\sigma_{Z\max}^2 + 3(k_\tau \cdot \tau_{\max})^2}\,(k_\tau{=}0.5) \tag{20}$$

### 2.6 Check the peeling force of thread

Peeling force of nut thread is:

$$F_{\mathrm{mGM}} = C_1 \cdot C_3 \cdot \tau_{BM} \cdot \frac{m_{eff}}{P} \cdot \left[\frac{P}{2} + (d - D_2)\cdot \tan 30°\right] \cdot \pi \cdot d \tag{21}$$

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In the form: $$R_s = \frac{d \cdot \left[\frac{P}{2} + (d - D_2) \cdot \tan 30°\right]}{D_1 \cdot \left[\frac{P}{2} + (d_2 - D_1) \cdot \tan 30°\right]} \cdot \frac{R_{mM}}{R_{mS}} \tag{22}$$

And $C_1 = 1$

If $0.4 < R_s < 1$ than $C_3 = 0.728 + 1.769 R_s - 2.896 R_s^2 + 1.296 R_s^3$

If $R_s \geq 1$ than $C_3 = 0.897$

the calculated peeling force of the thread is compared with the breaking force of the bolt thread of the free load ,the end result needs to meet: $F_{mGM} \geq F_{mS}$ ,In the form: $F_{ms} = R_m \cdot A_s$ .

$\tau_{BM}$ is the shearing strength of the base metal with internal thread, $D_1$ is the inner thread path, $D_2$ is the inner thread diameter, $R_{mM}$ is the internal thread base material tensile strength, $R_{mS}$ is the tensile strength of the bolt.

## 3 Flexibility Simulation

### 3.1 Simulation of bolt flexibility

Establish the connection model of the detailed thread as shown in Figure 1, application of Fix support on the bottom of Internal Thread Base material parts, the Displacement for which 0.001mm is applied to the bolt head as shown in Figure 4. Extracting the Force Reaction of this displacement load from head of bolt, the result of the solution is that the reaction force is 1138.9 N.

$$\delta = \frac{\Delta f}{F_{rea}} \tag{23}$$

Obtain the bolt flexibility 8.78×10$^{-7}$mm/N, The result calculated from VDI2230 is 8.71×10$^{-7}$mm/N, the error is 0.8%.

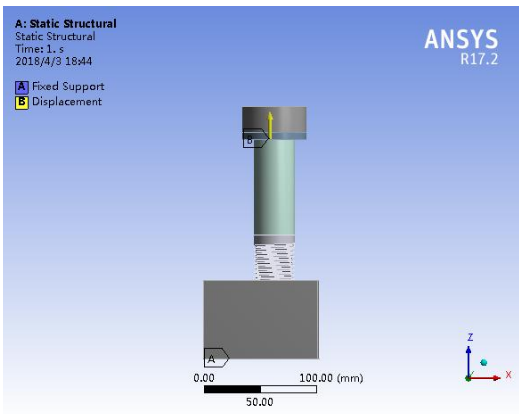


**Fig. 4.** The boundary condition of simulation

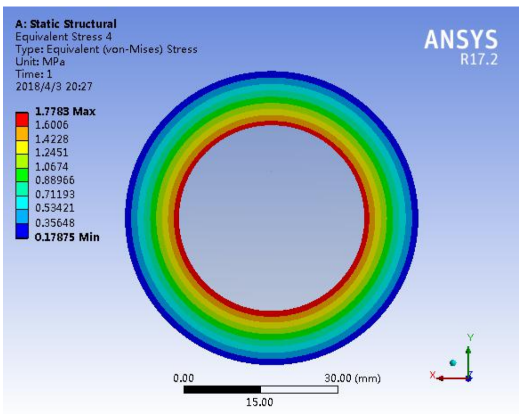


**Fig. 5.** The bolt head equivalent stress

### 3.2 Simulation of connector flexibility

Cut off part for flange ring, as shown in Figure 6, the size parameter is established according to the outer ring of the yaw bearing, the bolt elastic modulus is $2.05\times10^5$MPa, and the elastic modulus of the connecting piece is $2.06\times10^5$MPa.

Applied 0.3 mm downward displacement to the bolt, extracting the deformation and the Force Reaction on the connecting piece, the mean value of the shape variable on the surface is -0.000526mm.The reaction force is 7345.9N.The flexibility of the attached member is obtained to be $7.16\times10^{-8}$mm/N，The result calculated by VDI2230 is $7.18\times10^{-8}$mm/N, with an error of 0.28%.

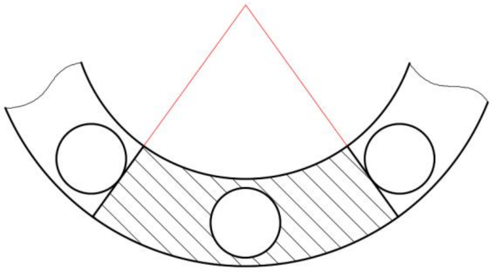

**Fig. 6.** The selected segments for simulation

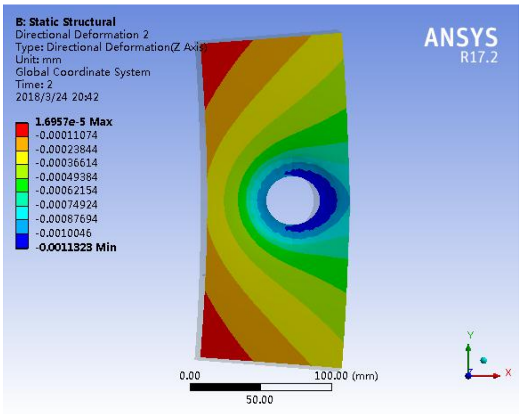


**Fig. 7.** The upper surface equivalent stress

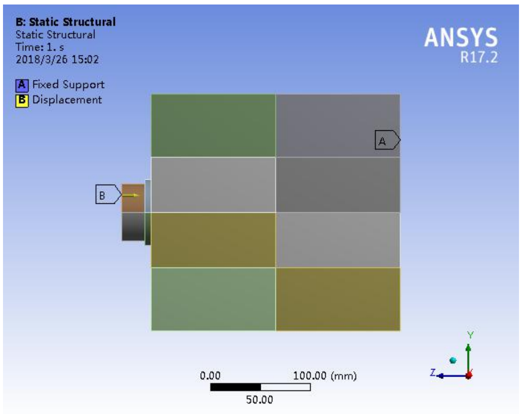


**Fig. 8.** The boundary condition of simulation

## 4 ESV internal thread peeling simulation

For yaw bearing outer ring bolt to do a pull-off simulation. First, a simulation model is established. In order to solve the problem more quickly, it is not necessary to apply pretightening force, but to apply tensile force on the supporting surface of bolt head, because of the analysis of bolt force and internal thread force. Remove the middle connector. A Path1 is established in the center of the bolt, and the edge line of the root of the inner thread is extracted to establish Path2. After the calculation is completed, the extracted Path1 stress, that is, the stress sustained by the bolt, and the Z direction stress on the extracted Path2, that is, the stripping force on the inner thread, are obtained. Apply tensile force to bolt head Force load, mesh As follows:

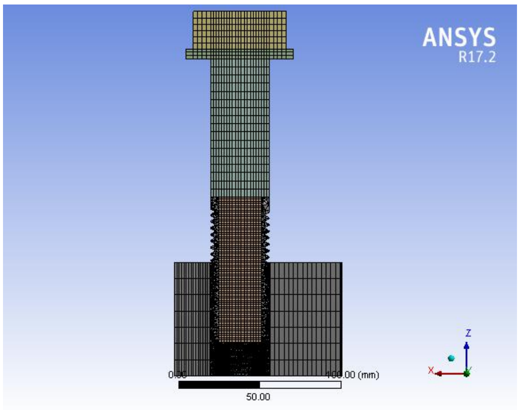

**Fig. 9.** The overall mesh

According to the calculation in VDI2230, the tensile force of the bolt is 817kN and the peeling force of the internal thread is 1273kN.When the bolt tensile force is applied 817kN, the extracted Path1 stress is 979.48 MPa (excluding stress concentration), below 1000MPa, and the error of calculation is 2%, the bolt can be broken, and the Z direction stress on Path2 can be extracted. The shear stress at the root of the internal thread is below 300MPa, which is lower than the shear strength of the base material 400MPa.

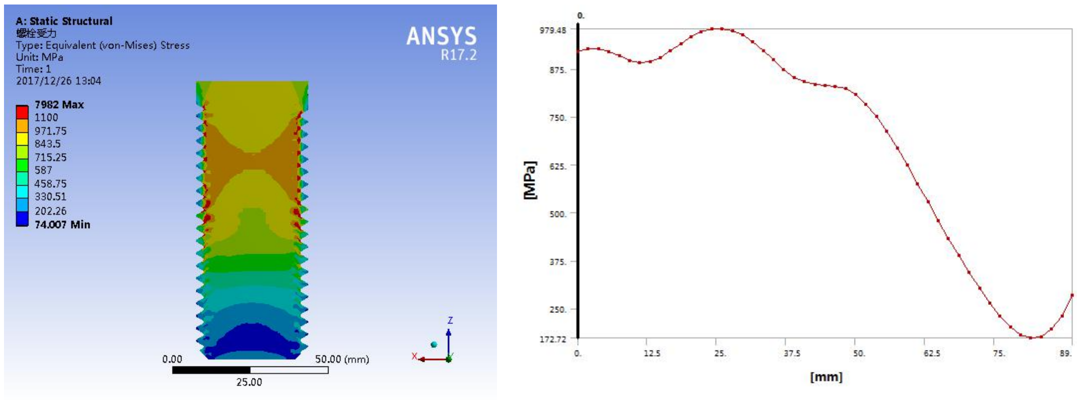


**Fig. 10.** The bolt thread internal equivalent stress with 817kN axial tension

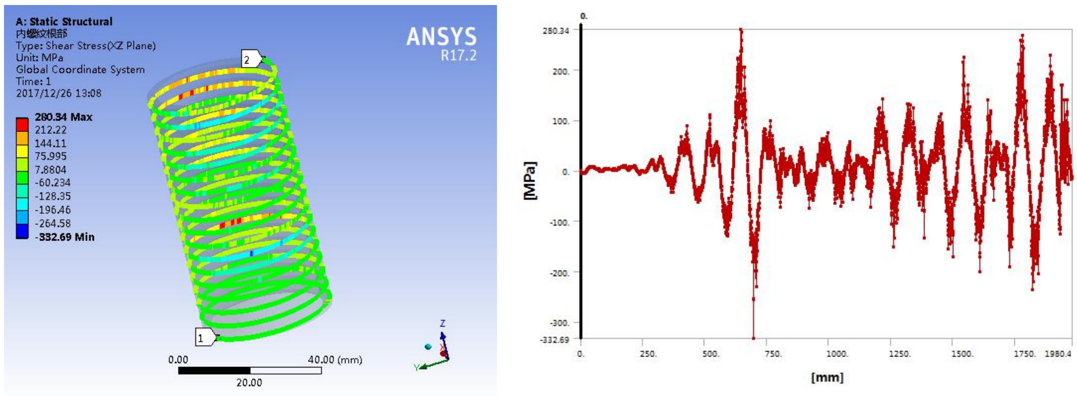


**Fig. 11.** Internal thread root shear stress with 817kN axial tension

Apply bolt breaking force to bolted head support surface 1273 kN. When the internal thread peeling force 1273kN is applied, the maximum stress (except stress concentration) inside the bolt is below 1527.6MPa, that is, the bolt can be completely broken under this condition, and the shear stress at the root of the internal thread is above 400MPa, which is higher than the shear strength of the base material. The internal thread can be peeled off at this time.

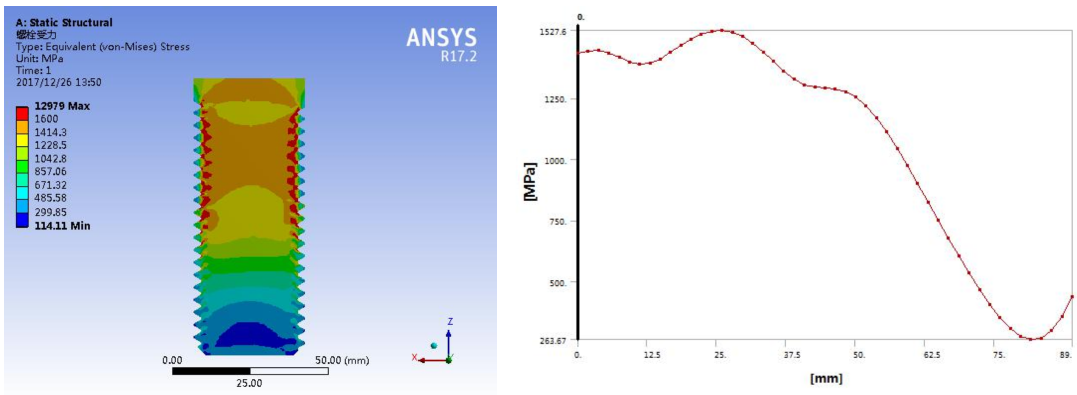

**Fig. 12.** The bolt thread internal equivalent stress with 1273kN axial tension

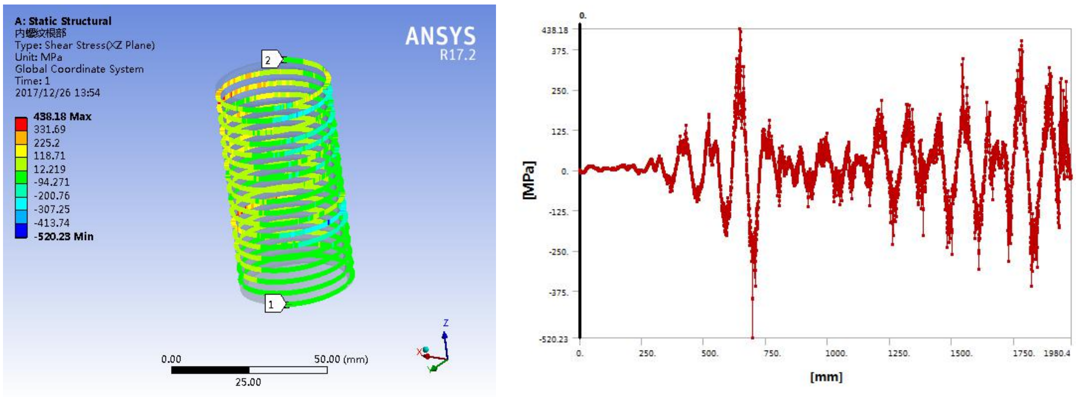


**Fig. 13.** Internal thread root shear stress with 1273kN axial tension

## 5 Conclusion

According to the calculation method of bolt by VDI2230, the simulation analysis method of multi-bolt flange connection is summarized, and the accuracy of bolt calculation result is verified by VDI2230. The main conclusions are as follows:

1) The result of bolt compliance calculated based on VDI2230 is 0.8% different from that of simulation analysis of bolt compliance. The difference of the connected parts is 0.28%, all results above are basically accurate.

2) There is only 2% error between the simulation results of internal thread peeling and calculation, the results are basically accurate.

3)The screw connection at this yaw bearing will only break the bolt under the unexpected load, and will not occur the failure form of the internal thread peeling.

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