Analysis on mechanical property of tensile bolt-ball joint with sealing plate in high temperature

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Abstract. Elastic-plastic solid finite element model of bolt-ball joint with sealing plate was established. The mechanical performance of bolt-ball joint in high temperature was performed with finite element analysis. The stress distribution, ultimate bearing capacity and failure mode of bolt-ball joint in high temperature were studied. The results show that bolt-ball joint is eventually damaged on the sealing plate by bent, and plastic penetrating zone along the thickness direction of sealing plate is discovered. The stress of screw threads is large, and stress of bolt ball is very small except the part near threads. The stress of bolt is large, but do not reach the yield strength. When the temperature higher, the ultimate bearing capacity of bolt-ball joint is smaller.

1. Introduction
As Chinese social economy is developing rapidly, the application of large-span space structure is more and more. Bolt-ball joints are widely used in spatial grid structure. In long-span spatial structures, joints are very important for the safety of the structure because of stress concentration of nodes. Once nodes fail, some or all of the bearing capacity of phase connecting members will be lose, than the force transmission paths may be changed, local structure system damage can be caused, and even the system continuity damage may happened.

As bolt-ball joints are applied widely, many experts and scholars have studied projects around the sealing plate mechanical properties, and abundant research results have been obtained. But most of the research is aimed at room temperature, and there are few studies about mechanical properties on bolt-ball joints in high temperature. In China, the general rule of the sealing plate is given in <technical regulations of steel net frame>[1] and <bolt ball node and space grid structure>[2], but the formula for calculation formula and bearing capacity of sealing plate thickness are not given. Cao[3]obtained the approximate value of the ultimate bearing capacity of the sealing plate by the theory of structural plastic analysis. Pan[4]conducted elastic-plastic analysis of sealing plate under static load by the axisymmetric finite element method, discussing the stress distribution, plastic zone development process, failure mode, and displacement’s effect on the bearing capacity of sealing plate. Finally he put forward the calculation formula of the two kinds of connection and design suggestions. Zhang[5] also fit bearing capacity formula of sealing plate of bolt-ball joints using numerical fitting method.

The bolt simulation is also studied. Fu [6] establish the finite element calculation model of bolt ball with ABAQUS software, and three-dimensional entity is adopted. Because the calculation of real bolt with screw-up thread is not easy to convergence, plane tooth screw is set on the bolt and bolt ball. When the helix angle of screw is less than 4°, the distribution of load along the thread tooth is almost not affected by the influence of the helix angle. Under the action of axial load, the bolt can be simplified into axisymmetric problem, and the validity and rationality of solution are generally accepted[7].
According to the fire statistics, many serious and extremely serious fires in China have been related to some form of large space buildings recent years[8], such as the fire of Friendship Hall of Karamay in Xinjiang Uygur Autonomous Region, the fire of Shenzhen AnMao Dangerous Goods Storage, the fire of transportation company Qingshui River Warehouse, the fire of Beijing Jade Island Furniture City and Liaoning Shenyang city, etc[9]. These fires have resulted in very serious results and great social impact, and the lives and property of the people have been severely damaged. In this paper, the elastic-plastic finite element mode of bolt-ball joint with sealing plate in high temperature is established by finite element software ANSYS to conduct calculation analysis, studying the failure mode of bolt-ball joint in high temperature, and obtaining the capacity reduction of bolt-ball joint with sealing plate in high temperature.

2. Finite Element Modes
Bolt-ball joint consists of bolt-ball, sealing plate, bolt and sleeve, and the bolt-ball is mostly made of 42CrMo steel whose tensile strength is 1080Mpa and yield strength is 930Mpa. In this paper, the sealing plate and steel tube are made of Q345 steel. The 10.9 high strength bolt is adopted, and the yield strength is 940Mpa. The sleeve do not work when the bolt-ball joint is in tension, so the sleeve can not be simulated. The basic size of bolt thread is shown in figure1. The specific dimension of thread on the M22 blot is shown in table1.

![Figure 1. Nominal thread size](image)

| D₁, d₁(mm) | P(mm) | D₂, d₂(mm) | D₃, d₃(mm) |
|------------|-------|------------|------------|
| 22         | 2.5   | 20.376     | 19.294     |

Based on the stress situation of bolt-ball joints, the following assumptions are made for the calculation model: The tension on bolt-ball joint is applied on the end of steel tube and is distributed on the tube section; The contact of screw cap and sealing plate is surface-to-surface contact; The threads of bolt and bolt ball contact surface-to-surface contact. The bolt ball can be simulated in half, and the screw is set as plane tooth screw. Because the overall model is axisymmetric and the meshing number of the threads is very large, 1/4 of the whole model is adopted to calculate.

The geometry parameters of sealing plate, steel tube and bolt in the bolt-ball joint are shown in figure 2, in which, D is the diameter of steel tube; d₁ is the bolt diameter; t is the thickness of seal plate; d₃ is the aperture diameter of sealing plate; d₃ = d₁ + 1 mm; d₂ is the diameter of nut which is related to d₁ according to standard [5]; a is the wall thickness of tube, and a=3mm; L is the length of tube, and L=50mm. Take D=54 mm, d₁= 22mm and t= 12mm to analyze.
Figure 2. Geometric parameters

The sealing plate, bolt, steel tube and bolt ball are established choosing advanced three-dimensional entity unit soild186, and the finite element model of bolt-ball joint is shown in figure 3. The steel tube and sealing plate are connected with the glue command. The expansion coefficient of steel in high temperature is selected from the standard of China and $\alpha_s=1.2 \times 10^{-5}$. The steel material properties in high temperature of European standard model [10] are used in this paper, and the poisson's ratio is 0.3. In this model, the ideal elastic-plastic material is assumed, and the material obey Von-Mises yield criterion.

In this paper, the uniform temperature load is applied on the model firstly, and the temperatures are 20°C, 200°C, 300°C, 400°C, 500°C, 600°C and 700°C respectively. Than the symmetric constraints are applied on the symmetric surfaces in figure 4, and the fixed constraint is applied on the base surface of the bolt ball. Finally the displacement is applied on the end of steel tube. In the analysis, material nonlinearity and geometric nonlinearity caused big deformation angle are considered.

Figure 3. Model of bolt-ball joint

3. Analysis of Finite Element Calculation Results

3.1. Load Displacement Curve

It is shown in figure 4 that the load displacement curves of bolt-ball joint at 20°C, 200°C, 300°C, 400°C, 500°C, 600°C and 700°C calculated by the finite element model, where the
displacement is the axial displacement at the end of the tube, and the load is the axial tensile load on the bolt-ball joint.

![Figure 4. Load displacement curves at different temperatures](image)

As figure 5 shows, the load-displacement curves of bolt-ball joint are linear and the bolt-ball joint is at the elastic stage when the displacement is small. With the increase of the displacement, the load increase slowly, and bolt-ball joint enters the elastic-plastic stage. As the displacement continues to increase, bolt-ball joint enters the plastic stage. Finally, The load reaches the ultimate load, and the load do not increases and even decreases as the displacement increases. The elastic stiffness of sealing plate in normal temperature is 1337 kN/mm; the elastic stiffness changes little in the temperature under 300°C; the elastic stiffness is about 938 kN/mm in 400°C and about 70.2% of that in the normal temperature; the elastic stiffness is about 416 kN/mm in 600°C and about 31.1% of that in the normal temperature; the elastic stiffness is about 174kN/mm in 700°C and about 13% of that in the normal temperature. As the temperature rises, the sealing plate goes into the elastic-plastic stage more and more early.

3.2. Load Bearing Capacity
As the temperature increases, the ultimate load of the conical head drop. The ultimate load changes very little when 20°C to 300°C. The ultimate load decreases significantly after 300°C and the falling speed is significantly faster after 500°C. The ultimate load in normal temperature is 171.45kN; the ultimate load in 300°C is 171.19kN and similar as that in normal temperature; the ultimate load in 400°C is 155.88kN and about 90.9% of that in the normal temperature; the ultimate load in 500°C is about 77.9% of that in the normal temperature; the ultimate load in 600°C is about 46.9% of that in the normal temperature; the ultimate load in 700°C is only 22.9% of that in the normal temperature. The main reason is that the elastic modulus of steel, yield strength and ultimate strength decrease with increasing temperature.

3.3. Failure Modes
The stress nephogram of bolt-ball joint is shown as figure 5. When the model is destroyed, the stress of the part connecting steel tube and sealing plate is larger. The plastic zone is formed on the center of outside surface of sealing plate, and the plastic through zone along thickness is formed on the sealing plate with the increase of load. The stress of screw threads is large, and stress of bolt ball except part near threads is very small. The stress of bolt is large, but do not reach the yield strength.
Figure 5. Mises-stress nephogram of small bolt-ball joint under 500°C

4. Conclusion
Temperature has large effects on the ultimate load of bolt-ball joint. As temperatures rise, the reduction factor of conical head ultimate load is more and more small. When 700°C, the ultimate load of conical head is only about 20.9% of that in the normal temperature. The plastic through zone along thickness is formed on the sealing plate when the model is destroyed.

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