Application of Cast Steel Joint in large-Span Steel Structure

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Abstract. Cast steel node is a new type of structure joint developed with the application of large-span steel structure. The stress distribution is discussed of cast steel nodes under three-dimension load by FEM, in the space grid structure of a hangar. By the measurement, the stress on the surface of the cast steel node under the design load is obtained. Combined with the test on-the-spot and computation, the result proves FEM result.

1. Project overview
Due to the integral casting of cast steel joint in the factory, not only various complex and elegant figure can be cast according to architecture shape, but also stress concentration caused by intersecting line cutting and overlapping seam welding can be avoided[1-3]. But there have been no standard design method and test method for cast steel joint, not to mention relevant norms.

A hangar has a longitudinal length of 156m, depth of 99.285m, maximal height of 36m, two continuous spans of 78m and single span of 96m. Roof is a bidirectional orthogonal quadrangular pyramid welded ball grid structure in a size of 5500mmx6000mm. The height of the grid structure is 6-3m in the first layer and 5.5-1.5m in the second. The dimension of the welded hollow ball is φ350x12mm-φ800x32mm in 7 types. The sectional dimension of steel tube is φ89x4.5mm-φ377x18mm in 15 types. Both the steel tube and steel ball adopt Q345B steel. The total weight of the grid structure is about 1200T.

2. Main features of the project
Main features of the project adopts a three-layer curve grid structure with a novel architectural style. Given the project adopts a rare three-layer curve space grid structure, the whole rigidity of the grid structure has been improved and member bar internal force peak reduced, hence lowering fracture.
surface of member bars. But on the other hand, due to large area of the grid structure, maximal height of 13m, large numbers of grid and welding, it is difficult to control welding stress and deformation.

In adapt to building configuration, the joint is dominated by welded hollow ball joints accompanied by cast steel joints. If welded hollow ball joints are adopted for the joints connecting the ball hinged support and the grid at the top of jack post ①×B and ⑧×B, then ball diameter will reach D1800mm, which will cause the following problems: 1) excessive large fracture surface of concrete column which support the joint; 2) difficulty in fabricating D1800mm welding ball; 3) it is difficult to accurately determine joint bearing capacity by experiments. So it is finally decided that cast steel joints will be adopted for the joints between grid and ball hinged support at the top of grid ①×B (ZZ-4A) and ⑧×B (ZZ-4). The elevation of cast steel joints and ball hinged support is shown in figure 3.

![Figure 3. Cast steel joint and seismic spheric joint support](image)

3. Cast steel joint design and calculation analysis

3.1. Cast steel joint design

The type of cast steel adopted is GS-20Mn5. In consideration of the wall thickness of cast steel joint is relatively big, the presupposed wall thickness being about 50-100mm, so set the compression resistance, tensile and bending strength design value \( f = 260 \) MPa, and shearing strength design value \( f_v = 145 \) MPa. Referring to the experience of important joint design in other projects, this stress ratio of cast steel joint is controlled to be 0.6. Equal strength groove butt welding is applied for connecting cast steel joint side tubes and structural steel tubes. Joint side tube is placed on the main side tube at the connection of joint tube and tube. There are 8 intersecting side tubes at the spherical crown of ZZ-4 joint, where there is a high requirement upon bearing and shearing strength. Therefore, stiffening ribs are added on main tubes at joint.

3.2. Computational analysis of cast steel joint

Solid modeling method is adopted in ANSYS, and the whole joint is treated as an integral, wherein main tube of ZZ-4A joint connects 8 steel side tubes and main tube of ZZ-4 joint connects 12 steel side tubes. SOLID45 is adopted for constructing 3D solid joints. There are 8 joints in the unit, and each unit has 3 transitional degree of freedom along the direction of X, Y and Z. Materials property: elastic modulus \( E=2.06e8 \) and Poisson's ratio 0.3.
Free grid division method is adopted, grid density can be adjusted according to construction of joints, by which the grids at the intersection of side tubes and the intersection between side and main tube are denser. That computation results are more accurate. The joint number of ZZ-4A joint is 12,016, and grid number is 37,657; the joint number of ZZ-4 joint is 23,967, and grid number is 83,270.

Inverted analytic model is adopted. Side tubes at the upper joints are fixated and hinged, and reverse resultant force is applied to the bottom slab. That bending moment is released; meanwhile the same stress for both joint and main tube.

3.3. Computational results analysis

Stress on ZZ-4A joint from all directions is as shown in figure2-figure8, normal stress value and shearing strength of main tubes meet the design requirement. The normal stress at the intersection of few side tubes and main tubes exceeds the design value of stress by 60%-96%. The normal stress and shearing strength of other parts are lower than 60% of strength design value. The stress bearing can meet the requirements after treating variable cross section and beveling of side tube bottom.

Figure 4. Y direction stress graph of joint ZZ-4A
Figure 5. -X direction stress graph of joint ZZ-4A
Figure 6. -Z direction stress graph of joint ZZ-4A
Figure 7. -Y direction stress graph of joint ZZ-4A
As shown in figure 9 to figure 13, normal stress value and shearing strength of main tubes meet the design requirement, and normal stress at the intersection of few side tubes and main tubes reaches 68%-79% of stress strength design value. Where normal stress value exceeds stress strength design value by 60% is concentrated in connection between side tubes and main tubes. The stress bearing meets requirements after treating variable cross section and beveling of side tube bottom.
Through computing and analyzing ZZ-4A and ZZ-4 cast steel joints, it is found out that with the same load, increased wall thickness of cast steel side tubes helps to reduce stress peak. For example, there are two side tubes 7J and 12H for cast steel joint ZZ-4; if the wall thickness of 7J and 12H is increased from 25mm to 30mm, there is a significant decline in stress peak.

As shown in calculated results, big stress values of joints are mainly concentrated in the intersection of side tubes and main tubes. That is the stress at beveling outside joint reaches the peak; hence presence of stress concentration; but far from the intersection, the stress drops sharply. Given no variable cross section and beveling treatment measures at computation analytic modeling, stress peak value is large at partial areas. In actual casting, variable cross section method is adopted for side tube casting, namely increase of thickness at intersection of main tube and side tube from 30mm to 50mm accompanied by beveling treatment. The stress bearing capacity of joints can be improved, so as to lower down stress peak value.

4. Field test of cast steel joint
According to finite element analytic results, positions with most concentrated cast steel joint stress (these measuring points are mostly located at the smooth curvy surface at the intersection of side tube and main tube) and complete data are chosen for strain test, with strain gauges stuck at corresponding points.

- Measuring point 16# at the position of maximum stress for ZZ-4A cast steel joint (in the smooth curvy surface at the intersection of 9AG side tube and main tube);
- Measuring point 12# of ZZ-4A cast steel joint (in the smooth curvy surface at the intersection of 10Q side tube and main tube);
- Measuring point 45# of ZZ-4 cast steel joint (in the smooth curvy surface at the intersection of 7J side tube and main tube);
- Measuring point 37# of ZZ-4 cast steel joint (in the smooth curvy surface at the intersection of 15(1) side tube and main tube).

To obtain the real test stress of cast steel joint [5], the strain value tested should be converted into stress value, so as to analyze the stress obtained through finite element computation and stress obtained through field test.

| Measuring point | Strain | Primary strain | Primary strain(MPa) | σ(MPa) Field test reduced stress | σ(MPa) Finite element computation value |
|-----------------|--------|----------------|---------------------|-------------------------------|----------------------------------------|
|                 | ε₀     | ε₄₅           | ε₉₀                 | ε₁                           | ε₃                                     | σ₁                        | σ₃                      | Field test reduced stress | Finite element computation value |
| 16#             | -220   | -710          | -150                | -711.1                       | 341.1                                  | 28.1                      | -133.9                 | 149.9                    | 197.4                       |
| 12#             | -180   | -620          | -120                | -640.1                       | 340.1                                  | 32.6                      | -85.4                  | 105.5                    | 154.5                       |
| 45#             | -200   | -680          | -140                | -680.9                       | 340.9                                  | 30.1                      | -127.3                 | 144.7                    | 188.6                       |
| 37#             | -148   | -540          | -122                | -540.2                       | 270.2                                  | 23.8                      | -101                   | 114.8                    | 132.3                       |

Compared field tests with ANSYS analytic results, it is indicated that the cast steel joint is in state of elasticity with sound stress bearing performance and sufficient safe storage. In conducting elasticity analysis of cast steel joint with ANSYS, there is certain difference between hypothesized boundary conditions and actual conditions due to the large rigidity of it. Meanwhile, the computation value also takes partial coefficient for load into consideration, so as to reflect that the maximal stress value of finite element analysis is larger than actual test value.

5. Conclusion
This paper, with a case study of hangar project, utilizes finite element software ANSYS to conduct elasticity finite element analysis of cast steel joints in roof grid. Meanwhile, field test is conducted of the stress bearing performance of cast steel joints, and the stress distribution rule is obtained. To better understand cast steel joints, real test stress value of joints is obtained through field test of large cast steel joints. After comparing with finite element computation results, stress distribution features of joints are also discussed.
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