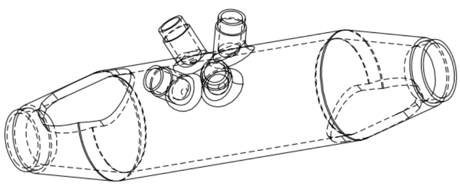
Recent Tests on Architectural Cast Steel Joints

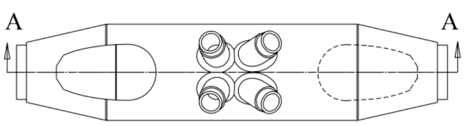
1. **Project:** Xuzhou Railway Station.

   Article Title: Research on KK-type Cast Steel Joint of Tension Truss at Xuzhou Railway Station [1].

   In this paper, in order to get the mechanical characters, the KK-type cast steel joint is studied by testing and finite element analysis methods. It considers that the cast steel joints have a high security reservation. By testing method, it suggests that at the construction site, when cast steel joint cut, welded, it should be avoided at a complex stress area and an area that bar cross-section changes. The proper distance away from the above area is at least 500mm. It also suggests that for cast steel joints itself, during the course of design and construction, the impaction of force of belly bar also should be paid attention.

   Finally, the bearing capacity of cast steel joints has been studied by the method of orthogonal test method. It conveys that the thickness of chord bar has more influences than others on the bearing capacity, but, the angle between the belly bar in the cross horizontal plane has the minimal impact. Through a rational parameter adjustment, the failure of the cast steel joint can be avoided and the purpose of design optimization is reached.





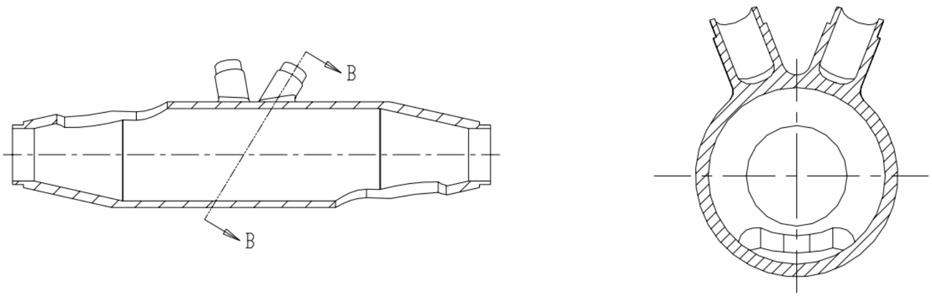


Fig.1. The geometric features of the KK-type cast steel joints [1]

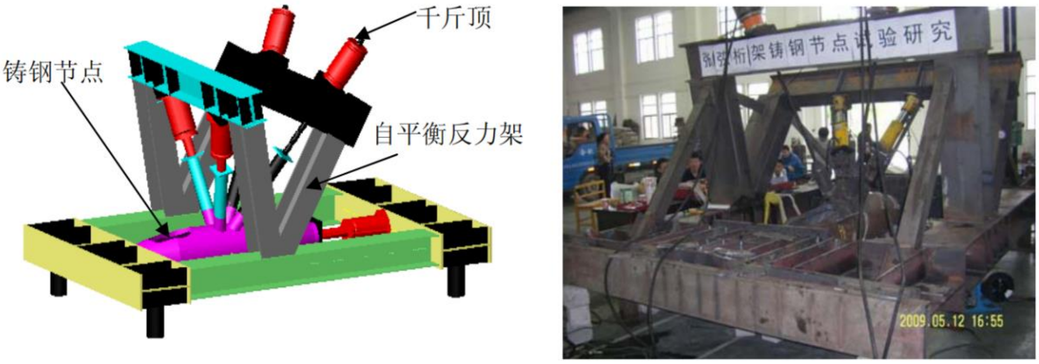


Fig.2. Diagram of the loading device and test [1]

2. **Project:** Hongqiao High-Speed Railway Station.

Article Title: Experimental Study on Cast-Steel Joints of Hongqiao High-Speed Railway Station [2].

In order to analyze the behavior and the bearing capacity of the cast-steel joints used in the Hongqiao high-speed railway station, the refine finite elemental analysis was conducted. Software SolidWorks was selected to calculate the finite elemental models. Then the stress distribution of the cast-steel joints was known, which indicates that the cast-steel joints have comparatively high load bearing ability and are safe enough. The full-scale experiments with well-designed reaction frames were done in the laboratory, which verify the reliability of the results of the refine finite elemental analysis. The optimization designs of the cast-steel joints were also done, and the proposals to reduce the total weight of the cast-steel joints were put forward.

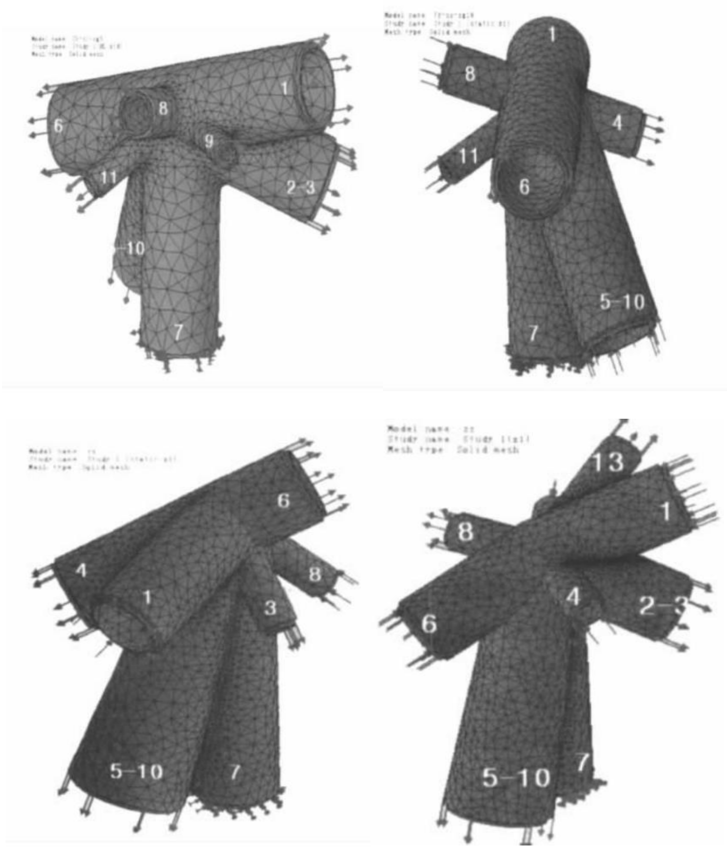


Fig.3. Models of four cast steel joints [2]

Fig.4. Diagram of the test [2]

3. **Project:** Hangzhou East Railway Station.

Article Title: Research on Static Behavior of the Plate Cast-steel Joint by Full-scale Test [3].

Through the full-scale test and finite element analysis, the plate case-steel joint, used in canopy without pillars on the platform in Hangzhou Dong station, which mechanical performance was researched under four directions axial forces. By comparing the calculated surface stresses with those obtained from the experiment, the whole stress distribution of the cast-steel joints was got. By contrasting the bearing capacity and evaluating the safety by yield criterion, it shows that the joint bearing capacity does not depend on the central basis. Test results show that the evaluation by FEM method was validated and the bearing capacity of cast-steel joint is high.

By analyses and compared of the static nonlinear finite element analysis model, of two kinds joint under the test conditions; the yield process of the cast steel joint and the central rainwater pipe's impact on ultimate bearing ability are get. Orthogonal test based on the finite element model, analysis of the differences of structure parameters' contribution to the ultimate bearing capacity, and optimize the cast steel joint design parameters. The results showed that: the rational allocation of the structural parameters of the cast steel nodes, to optimize the design.

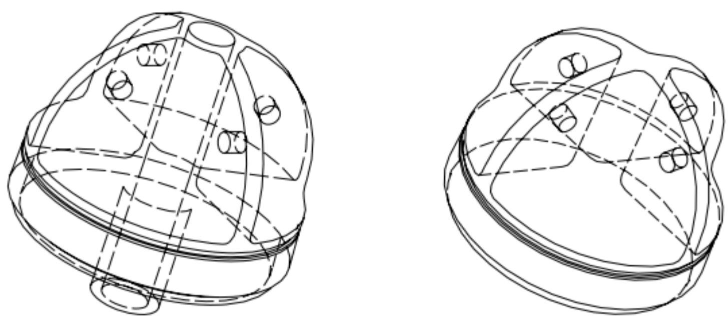


Fig.5. The geometric features of two cast steel joints [3]

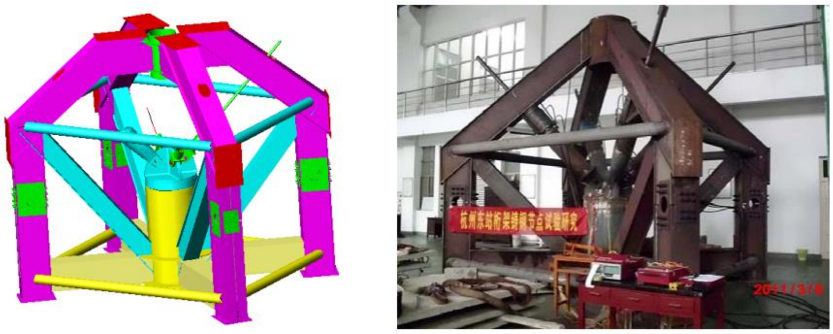


Fig.6. Diagram of the loading device and test [3]

4. **Project:** Tianjin Library.

Article Title: Theoretical Analysis on Main Steel Structure of Tianjin Library and Study On Important Joints [4].

The general development and application situations of steel frame-supporting system, tube-truss structure system and concrete-filled steel tubular joints are introduced at the beginning. Then the engineering background of the subject is described, followed with the main research content. Tianjin library possesses a unique architectural structure with a complex load transmission. The main structure adopts a complex steel structure system as a combination of steel frame-supporting system and intersected trusses, and the structural design is finished. A series of Finite Element Analysis are conducted to research the mechanical performances of this structure.

According to the force characteristics of the main steel structure, type selection and design of joints are accomplished. Finite Element Analysis of typical joints are performed to evaluate their mechanical properties. Two representative forms of cast steel joints are selected, and the theoretical analysis and experimental study of their mechanical properties are complimented. By comparative analysis of theoretical and experimental studies, the bearing capacity of cast joints under design loads are guaranteed, the rationality of both methods of theoretical analysis and experimental study is proved

Finally, the performances of the main steel structure during the load converting process in construction is studied with Finite Element Analysis. By contrasting local monitoring results and theoretical results of structure stress and deformation, the strength and stiffness level of the main steel structure are estimated, to support load converting scheme, and to ensure a successful construction period as well.

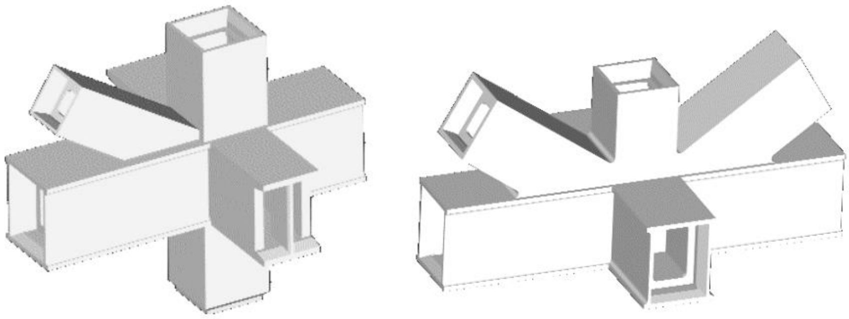


Fig.7. Models of two cast steel joints [4]

Fig.8. Diagram of the test [4]

5. **Project:** Nanchang West Railway Station.

Article Title: Experimental Study on Static Behavior of Y-type Cast Steel Joint in West Nanchang Railway Station [5].

This paper through the full-scale model tests and finite element analysis of Y-type cast steel joints in West Nanchang Railway Station. Mechanical performance was researched under bidirectional moment and axial force. Analysis of the entire node stress distribution can be known. Comparing the test results and the calculated contrast showed that: The Workbench software can effectively simulate the stress state of the joints. West Nanchang Y-type cast steel joint was safe and reliable.

Article establish the static nonlinear finite element analysis by Workbench. Analysis and comparison were made to know the difference of the bearing capacity between the two kind joints. And further analysis was also token to know how moment affect the cast steel joint by ultimate bearing capacity. The result showed that: the presence of rainwater pipes affected the bearing capacity of the cast steel joint very little. The presence of moment affected the ultimate axial bearing capacity largely.

Finally, the node analysis of orthogonal test, analyzed the difference of effect of each parameter on load-carrying capacity limit. The orthogonal test results showed that: different structural parameters of the bearing capacity of the ultimate contribution degree each are not identical, influence of the branch pipe wall thickness, the wall thickness of the pipe, and the intersection of the chamfer is in the third position, and the branch pipe and water pipe chamfer is minimal impact. In the design of Y node, reasonable allocation of these parameters, positive adjustment, in order to ensure the performance of nodes at the same time, improve the economy of the cast steel join.

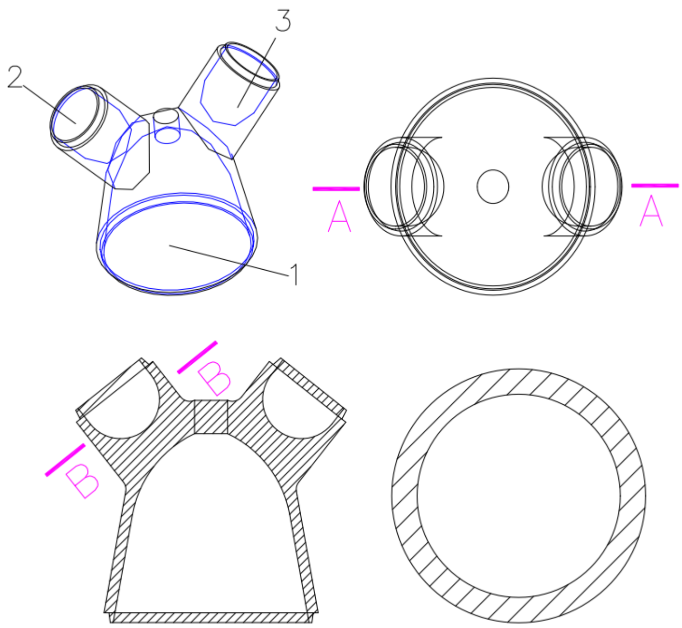


Fig.9. The geometric features of the Y-type cast steel joint [5]

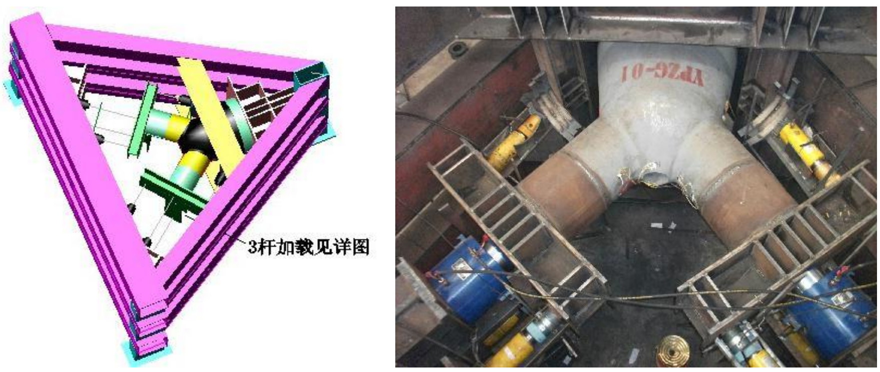


Fig.10. Diagram of the loading device and test [5]

6. **Project:** Chuzhou Middle School Gymnasium.

Article Title: Experimental Study on the Static Performance of Special-shaped Cast Steel Joints [6].

In this paper, the special-shaped cast-steel joint in steel roof structure of Chuzhou gymnasium was simulated and analyzed by the full-scale model test and numerical simulation. The mechanical property of special-shaped cast-steel joint in 7 different direction axial force was studied. By comparing the node full-scale model test and FEM simulation results the reliability of the simulation results was proved, and special-shaped node stress distribution was obtained. By selecting the ultimate failure criterion, the safety bearing capacity of node was evaluated by using the finite element software. By comparing the safety bearing capacity of Ordinary steel node and cast-steel node it proved that the safety reserve of cast-steel node was higher. By the application of orthogonal test method, 9 node models with different wall thickness, the angle and the radius were designed. Through to compare and analyze the limit bearing capacity of models, the influence of different parameters on the bearing capacity of the node was summed up.

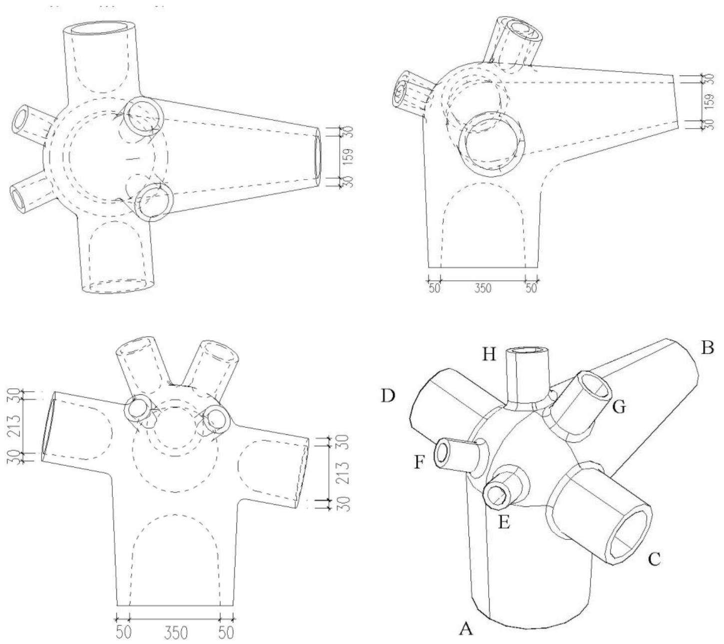


Fig.11. The geometric features of special-shaped cast-steel joint [6]

Fig.12. Diagram of the loading device and test [6]

7. **Project:** Yangtze River Channel No. 6 Model Test Hall.

Article Title: Testing Research on Bearing Capacity of the Cast Steel Ball Joints of 120m-span Model Test Hall [7].

The test of the cast steel ball joints of 120m-span model test hall was introduced, and full-scale loading tests for the cast steel ball joints were completed, so as to the simulation by ABAQUS. The bearing capacity supplied by experimental and simulation results with elastic analysis for cast steel ball joints was assessed comprehensively. The test results show that the cast steel ball joints are reliable and safe.

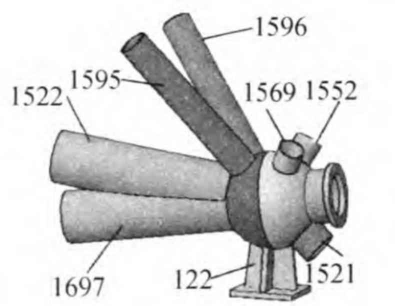


Fig.13. Model diagram of cast steel joint [7]

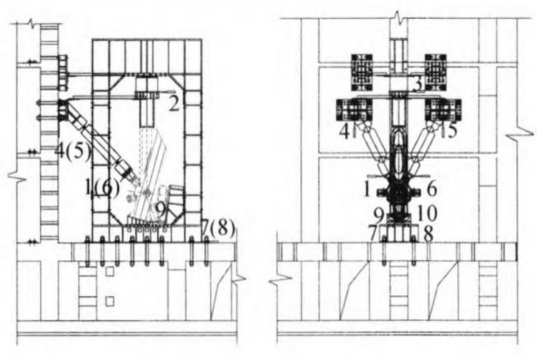


Fig.14. Diagram of the loading device [7]

8. **Project:** Chongqing Jiangbei International Airport.

Article Title: The Finite Element Analysis of Chongqing Jiangbei Airport T3A Typical Cast Steel Joints [8].

The cast steel joints of this paper are derived from the new airport terminal building in Chongqing Jiangbei Airport. Its space form is very different and the stress is relatively complex, therefore, it is necessary to analyze the mechanical properties of the grid nodes. Firstly, the stress distribution and deformation of the joint region are analyzed by ANSYS finite element software, as a basis for judging whether it meets the requirements of actual engineering design. Secondly, load displacement curve deformation, stress and deformation cloud were obtained by gradation loading. Then, some failure characteristics of the joints are further studied. Finally, some suggestions are put forward to optimize the use and construction process of this type of cast steel joints.

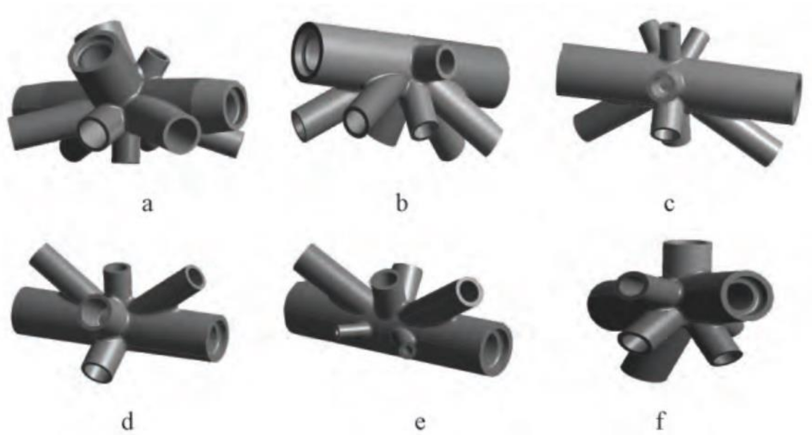


Fig.15. Model diagram of six cast steel joints for terminal T3A [8]

Fig.16. The joint specimen [8]

9. **Project:** Xinjiang International Convention and Exhibition Center.

Article Title: Experimental study of cast steel joint in truss string structure of Xinjiang International Convention and Exhibition Center [9].

In order to study the load-carrying capacity of a cast steel joint in the truss string structure of Xinjiang International Convention and Exhibition Center, loading test on the cast steel joint with 1/2 scale is conducted. It is revealed that the load carrying capacity of the test joint can satisfy the requirement of the most unfavorable design load combinations. The elastoplastic finite element analysis of the cast steel joint specimen is carried out, revealing good agreement between experimental and numerical results; hence the reliability of the finite element model is validated. Based on the obtained experimental and numerical results, the load carrying capacity and corresponding safety margin are both assessed, so as to provide the reference for design of cast steel joints in truss string structures.

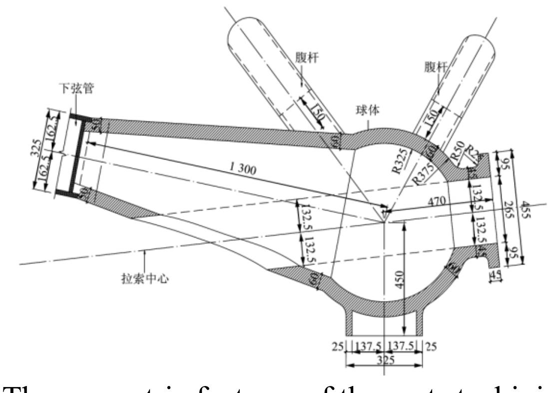


Fig.17. The geometric features of the cast steel joint [9]

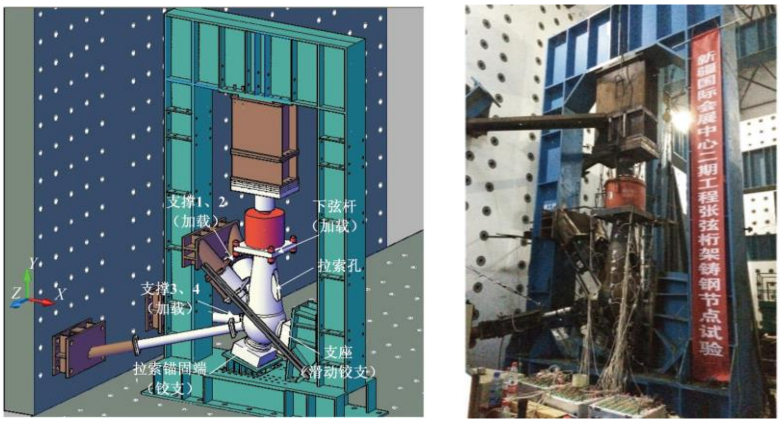


Fig.18. Diagram of the loading device and test [9]

10. **Project:** Wuhan Tianhe International Airport.

Article Title: Experimental study on mechanical behavior of cast steel joints in T3 terminal of Wuhan Tianhe International Airport [10].

In order to study the mechanical behavior under the most unfavorable design conditions of the cast steel joints in the grid structure in T3 terminal of Wuhan Tianhe International Airport, full-scale loading test and finite element analysis were conducted on the typical cast steel joint FLQ-35 A. Based on the test results, it can be found that the cast steel joint exhibits elastic behavior under 130% design load condition. There was no obvious residual deformation after unloading. It shows that the results of experiment and finite element analysis agree well with each other. The local plastic development at the variable cross-section of G1 pipe resulted in the failure of the joint. The ultimate bearing capacity of the cast steel joint meets the relevant requirements in the *Technical Specification for Application of Connections of Structural Steel Casting* (CECS 235: 2008). The designed cast steel joint has a relatively high strength reserve.

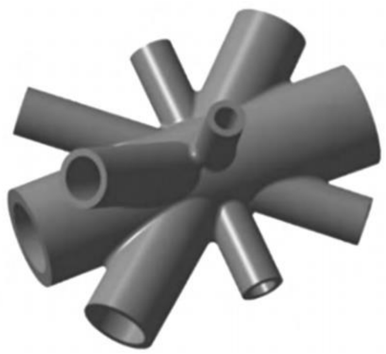


Fig.19. Model diagram of cast steel joint [10]

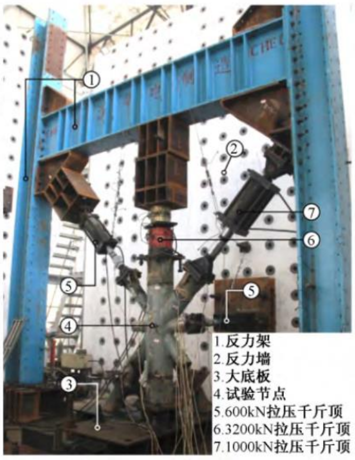


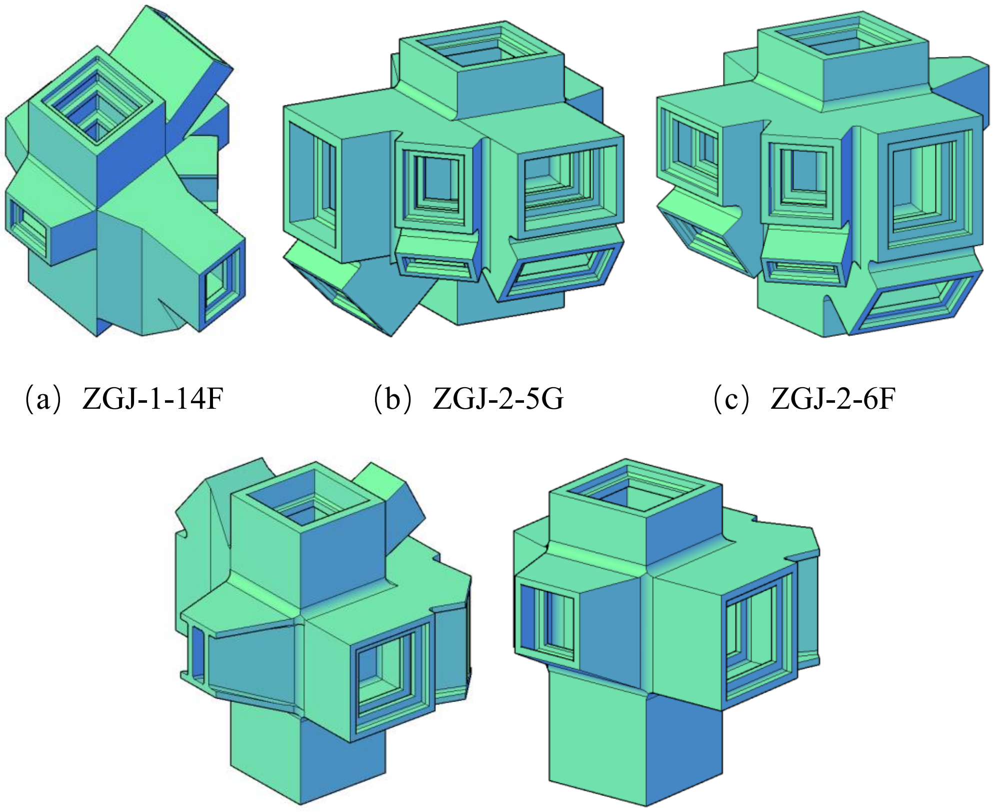
Fig.20. Diagram of the test [10]

11. **Project:** Hubei Science and Technology Museum.

Report Title: Hubei Science and Technology Museum Cast Steel Joint Test Report [11].

Cast steel joints were utilized in the Hubei Science and Technology Museum project. Given the complexity of such joints, which include multiple intersecting members, their large size, and the significant forces exerted on the connected members, it was deemed necessary to conduct scaled-down model tests to verify the safety of these joints. According to design requirements, scaled-down tests at a 1:2.5 ratio were performed on five typical cast steel joints: ZGJ-1-14F, ZGJ-2-5G, ZGJ-2-6F, ZGJ-3-14F, and ZGJ-3-15Q. When the load was increased to three times the design load, only individual measurement points reached a plastic state, while the overall joints remained elastic. Thus, these five types of cast steel joints are safe under the design load within the monitored range and possess a certain safety margin.

These reports also present finite element simulation analyses of the cast steel joints. The results indicate that under twice the design load, the joints remained in an elastic state. At three times the design load, only the corner regions of the cast steel joints entered a plastic state, confirming that the joints are safe.



(a) ZGJ-1-14F (b) ZGJ-2-5G (c) ZGJ-2-6F

(d) ZGJ-3-14F (e) ZGJ-3-15Q

Fig.21. Model diagram of cast steel joints [11]

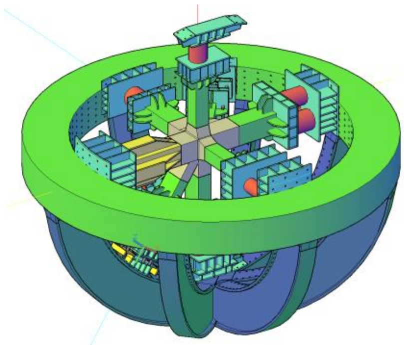
 

Fig.22. Diagram of the loading device and joint specimen [11]

12. **Project:** Huangshi Olympic Sport Center.

Article Title: Experimental Study on the Mechanical Behavior of Cast Steel Joint Used in Huangshi Olympic Sports Center [12].

Cast steel joints are introduced into the dendriform roof structure for the Huangshi Olympic Sports Center. Full scale test and nonlinear finite element (FE) analysis are carried out to investigate the mechanical behavior of the cast steel joints under the most unfavorable design load condition. The results indicate that the cast steel joint exhibits elastic behavior up to 130% design load, and no residual deformation after unloading is observed. The FE results agree well with the test data, and the ultimate load-bearing capacity of the cast steel joint obtained from the elastic-plastic FE analysis satisfies the relevant requirements from the *Technical Specification for Application of Connections of Structural Steel Casting*, with relatively high strength reserve being achieved. Moreover, the stress distribution pattern of cast steel hollow spherical joint subjected to axial load and bending moment is analyzed, and this provides reference for the design of cast steel hollow spherical joints.

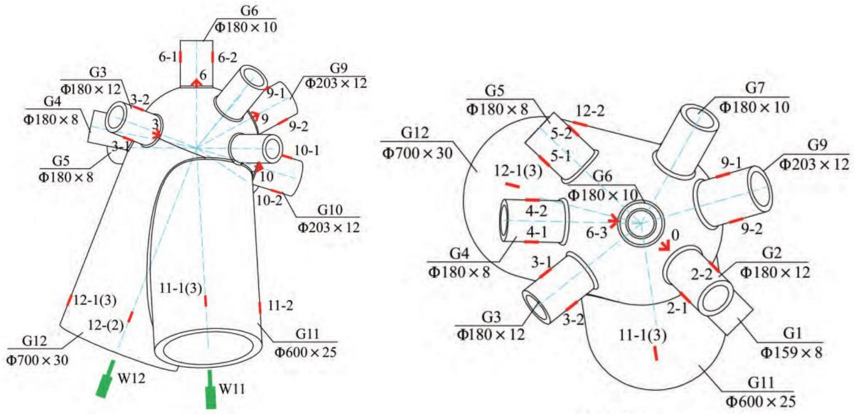
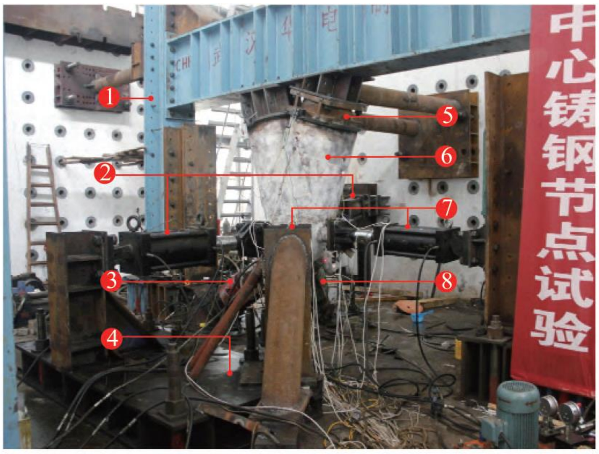


Fig.23. Measuring point layout of cast steel joint [12]



1—反力架；2—1 000 kN伺服作动器；3—3 000 kN千斤顶；
4—垫板；5—球铰；6—试验节点；7—600 kN伺服作动器；
8—2 400 kN千斤顶；

Fig.24. Diagram of the test [12]

13. **Project:** Kaifeng Yadong Zhonghong Hotel.

Article Title: Bearing capacity of the cast-steel joint with branches under eccentric load [13].

In this paper, by using the means of numerical simulation and experimental verification, mechanical behavior of three-branch cast-steel joints in the tree-like column structure under eccentric load was studied. A typical full-scale cast-steel joint with three branches was first tested under eccentric loads. Numerical analysis of the cast-steel joint with three branches under eccentric load was then carried out through

ANSYS and SolidWorks. Failure mechanisms of this kind of joint were analyzed and the main failure mode was summarized. Finally, the formula for predicting load carrying capacity of the cast-steel joint with branches under eccentric forces was proposed. The results showed that the failure mode of the joint under eccentric load is the buckling failure at the end of the compression side of the main pipe, and the formula based on the main failure mode is applicable in engineering and building designs.

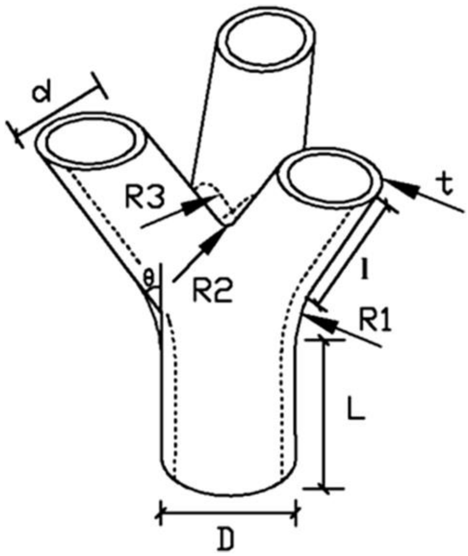


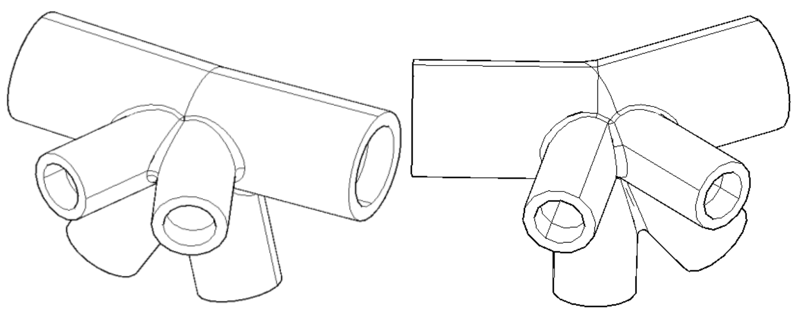
Fig.25. Geometrical features of the joint [13]

Fig.26. The loading device and joint specimen [13]

14. **Project:** Pedestrian Bridge of Jinshajiang Road and Zhenbei Road in Shanghai.

Report Title: Cast Steel Joint Test Report for Jinshajiang Road and Zhenbei Road Pedestrian Bridge Steel Structure Project [11].

This article evaluates the safety performance of two types of cast steel joints used in the pedestrian bridge at the intersection of Jinshajiang Road and Zhenbei Road in Shanghai: cast steel joints number 128 and 146. The article conducts loading tests on the two cast steel joints, obtaining stress values at various measurement points. It was found that under the design load, all measurement points remained in the elastic stage. Even when loaded to 1.3 times the design load, all points stayed elastic, indicating that the joints are safe under design loads and possess a certain strength reserve suitable for engineering applications. Furthermore, finite element analysis was used to obtain stress values at the experimental measurement points. By comparing these values with the stress test values, the accuracy of the finite element analysis model was validated. This model was then used to calculate and infer the stress conditions throughout the entire cast steel joint. Simulation results show that under 1.5 times the design load, the overall stress on the cast steel joints is very low, confirming the designed cast steel joints have a relatively high strength reserve.



(a) No.128 cast steel joint (b) No.146 cast steel joint

Fig.27. Model diagram of cast steel joints [11]

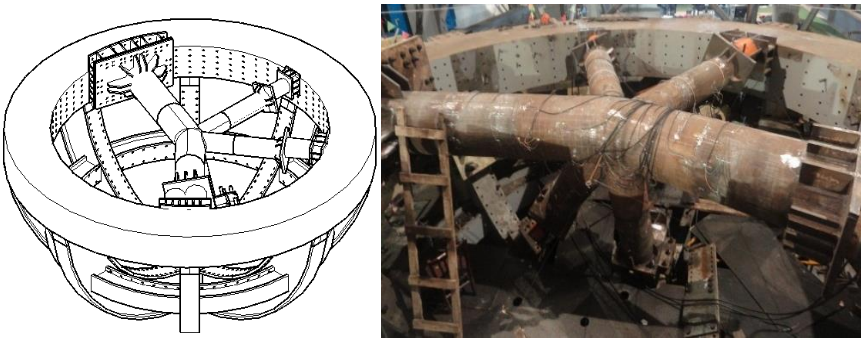


Fig.28. The loading device and joint specimen [11]

Model uncertainty refers to the variability in the resistance of structural components caused by the basic assumptions used in calculating resistance and the approximations in the bearing capacity formulas [14]. For rolled steel components, this mainly refers to the comparison between experimentally measured stress values and the results calculated from bearing capacity formulas. For cast steel joints, their resistance cannot be directly calculated using bearing capacity formulas, except for those with regular shapes. The finite element method is used for determining the bearing capacity in designing cast steel joint. Hence, the method for calculating the uncertainty parameters of the model for cast steel joints effectively becomes a comparison between experimentally measured Mises stress values at the certain points and the corresponding Mises stress values at the same locations in the finite element simulation [15], as shown in the following Eq.(1):

$$X_{\mathrm{P}} = \frac{R_0}{R_{\mathrm{c}}} \tag{1}$$

Where R_0 is the stress measured at a certain point in the joint test, R_{c} is the stress value at the location corresponding to the measured point in the finite element analysis.

This paper summarized the relevant articles [1–13], conducted a statistical analysis of the model uncertainty parameters for cast steel joints. When filtering data from the literature, it is necessary to exclude measurement points that are explicitly identified as erroneous in the literature or experimental reports. Considering that when the measured strain is small, the strain data collected by the equipment may have significant errors, measurement points with excessively small Mises stress values (e.g., smaller than 20 MPa) were also excluded [15]. Ultimately, from a total of 13 articles, data for 21 cast steel joints comprising 122 measurement points were compiled. The experimental measured values and finite element simulation results from the literature were compared to determine the model uncertainty, with the data sources shown in Table 1. The data included those in the elastic range as well as those in the plastic range, and the statistical assessment is capable of providing a comprehensive evaluation of the model uncertainty related to finite element simulations.

Table 1 Data sources of model uncertainty X_P

Project	Number of joints	Number of measurement points
2010 Xuzhou Railway Station [1]	1	11
2011 Hongqiao Railway Station [2]	2	9
2012 Hangzhou East Railway Station [3]	2	6
2012 Tianjin Library [4]	3	8
2013 Nanchang West Railway Station [5]	1	12
2014 Chuzhou Middle School Gymnasium [6]	1	6
2014 Yangtze River Channel No. 6 Model Test Hall [7]	2	14
2016 Chongqing Jiangbei International Airport [8]	1	5
2017 Xinjiang International Convention and Exhibition Center [9]	1	3
2018 Wuhan Tianhe International Airport [10]	1	7

2019 Hubei Science and Technology Museum [11]	4	28
2019 Huangshi Olympic Sport Center [12]	1	7
2019 Kaifeng YadongZhonghong Hotel [13]	1	6

The mean of X_P is 1.02, and the coefficient of variation is 0.153. The distribution of X_P is shown in Fig.29, and it conforms to a log-normal distribution under the K-S test with a significance level of 0.05.

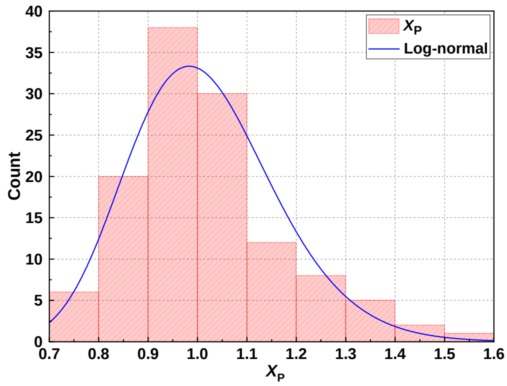


Fig.29. The distribution of the statistics of model uncertainty X_P

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