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Bearing capacity of the cast-steel joint with branches under eccentric load

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ABSTRACT

Bearing capacity of cast-steel joint with branches in a tree-like column structure is important when adopted, since failure of the joint will surely lead to the collapse of its whole superstructure. 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.

1. Introduction

Tree-like column based on the principle of bionics is more and more widely used in long-span spatial structures because of its novel and beautiful structural configuration, excellent bearing performance, and magnificent ability of wide coverage [1–2]. The representative projects include the Stuttgart Airport in Germany (1991), the Detroit Airport in USA (1996), the Portugal East Station in Lisbon (1998), the Stansted Airport in London (1999), the Shenzhen Cultural Center “Golden Tree” in China (2006), the ION Orchard Mall in Singapore (2009), Shenzhen North Station (2011), and Tianjin International Airport terminal building in China (2014).

Joint is the key part of the tree-like column structure. In order to realize the smooth transition among the main pipe and all branches, the joint in the tree-like column is generally made of the cast-steel joint with branches [3–4]. On the one hand, the welding location between the joint and components can be moved out of the joint area. On the other hand it can reduce construction difficulty and improve safety. However, the tree-like column structure is connected through a single joint at each level branch. The failure of the joint will surely lead to the collapse of its superstructure. It is therefore important to study the bearing capacity of this type of joint.

Theoretical analysis of the cast-steel joint with three branches was carried out by Sun [5]. Finite element analysis of the joint using the software of SolidWorks and ANSYS was conducted and the mechanical responses of the joint under axial load were obtained. Construction of the tree-like column structure was studied by Tan [6], in which selection of materials and dimensions, fabrication, installation and other technical problems about the joint were discussed. A summary of research and application of connections of structural steel casting was published in 2010 [7], in which important issues on structural design of cast steel connections including material properties, design criteria, theoretical and experimental analysis were addressed. Recently, more researches were geared to local yielding, fracture, and fatigue of cast steel joint connections, such as [8–11]. Loading analysis of the cast-steel joint with three branches was studied by Wu et al. [8]. Influencing factors on the performance of the joints were analyzed and the formula predicting capacity of the cast-steel joint with three branches was derived. Yielding in the cast steel yielding brace system for concentrically braced frames were discussed in [9]. Balanced fatigue design of cast steel nodes in tubular steel structures was discussed in [10], in which the allowable initial crack size was obtained. Stiffness requirement was discussed in [11], in which the method to correctly evaluate the joint stiffness was suggested.

However, these studies are purely on theoretical analysis or purely on experimental results of cast-steel joints with branches, which have no relevant experiment verification or no connection between the theoretical and the experimental results. Moreover, in practical engineering applications, it is difficult to achieve that the joints only bear the axial forces under the action of various load conditions. Therefore, in this paper, loading test of a typical full-scale cast-steel joint with three branches under eccentric load was first carried out. Mechanical

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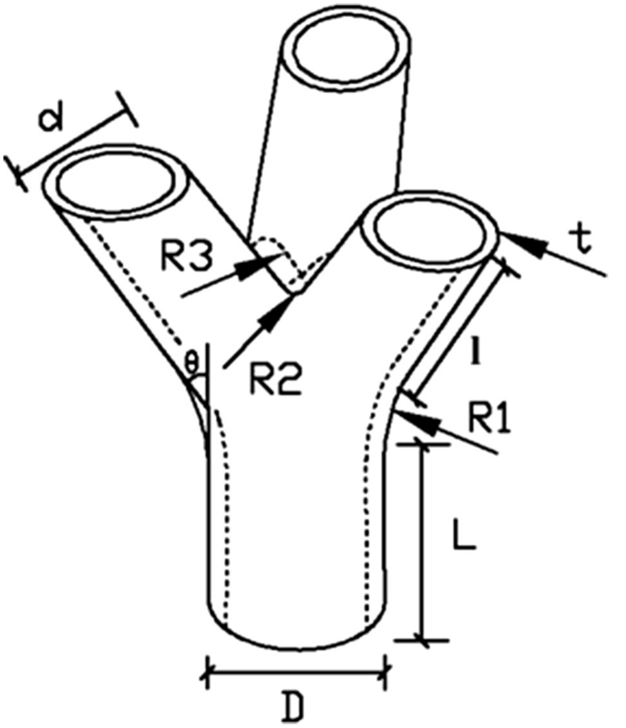

Fig. 1. Geometrical features of the joint.

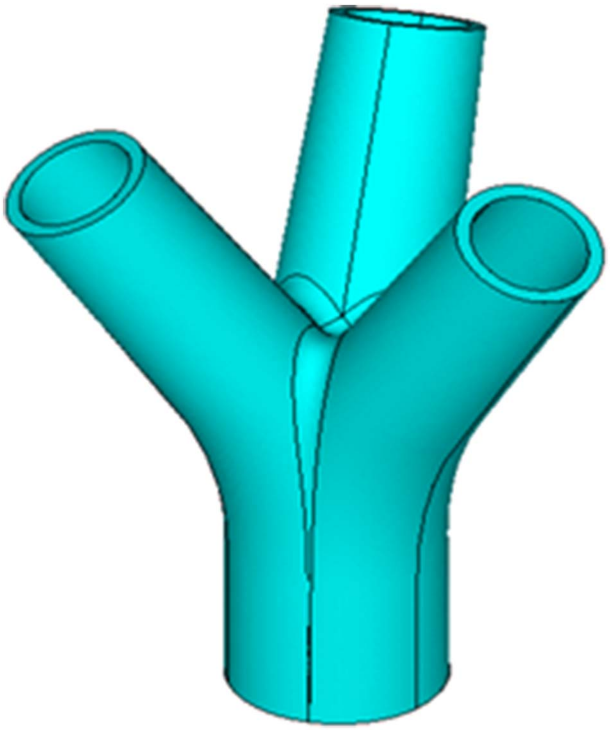

Fig. 2. The smooth joint model completed through SolidWorks.

responses of the cast-steel joint with branches under eccentric load were then studied by the finite element analysis. The stress distribution and failure modes of the joint were summarized, and compared with the experimental results. In the end a set of practical calculation formula based on the main failure modes of the joint was proposed to predict its bearing capacity.

2. Geometric parameters of the joint model

The cast-steel joint with branches is made of concurrent intersection by a main pipe and multiple branch pipes. Geometric parameters affecting its mechanical performance include the angle (θ) between the main pipe and branch pipes, the main pipe length (L), the main pipe diameter (D), the main pipe wall thickness (T), the branch pipe length (l), the branch pipe diameter (d), the branch pipe wall thickness (t), the chamfer radius (R_1) between the main pipe and the branch pipes, the outside chamfer radius (R_2) between the branch pipe and the branch pipe, and the inside chamfer radius (R_3) among the branch pipes. The geometrical features of the joint are shown in Fig. 1.

A practical project, the lobby of Zhonghong hotel in Kaifeng of China, is taken for reference in this paper. In the four tree-like columns to support a large span roof which covers an area of 24 m × 12 m, there are two level branches in each one to suit for the 6 m net height. The cast-steel joint with three branches was used at the connection between the trunk and the first level branch pipes. The geometric parameters are $\theta = 30^\circ$, $L = 800$ mm, $D = 500$ mm, $T = 40$ mm, $l = 1200$ mm, $d = 350$ mm, $t = 35$ mm, $R_1 = 1000$ mm, $R_2 = 20$ mm and $R_3 = 50$ mm. Two derived parameters are worth mentioning since they have important influences on the performance of the joint. One is the outer diameter ratio between the branch pipe and the main pipe ($\beta = 0.7$). The other is the ratio between the outer diameter of the main pipe and its wall thickness ($\gamma = 20$).

It is difficult to realize smooth transition of the joint in the numerical joint model by using common finite element software. SolidWorks is adopted to solve this problem and realize the smooth transition between the branch pipes and the main pipe (Fig. 2).

3. Experimental study

3.1. Manufacturing the joint specimen

The material of the joint is ZG20SiMn cast steel in which the content of C is 0.18%, the content of Si is 0.60%, the content of Mn is 1.50%, the content of P is 0.020%, the content of S is 0.015%, the content of Cr is 0.30%, the content of Mo is 0.15% and the content of Ni is 0.40%. The joint specimen was produced by Xinxiang Tengfei Factory in China, and transported to the structural laboratory of Henan University for test.

In order to control the relative error between the real size and the design size of the joint, the size of the actual joint is measured. And the relative error between them is listed in the Table 1. The maximum value of relative error is 2.80% (less than 5.00%), which shows all of them satisfy the design requirements.

A standard testing specimen is made for characterizing the cast-steel material properties [8]. The typical stress-strain relationship of the cast-steel coupon is shown in Fig. 3. There is an evident yielding plateau in the stress-strain curve according to the material test results. It shows the yield strength is 235.7 MPa and the ultimate strength is 353.6 MPa. The percentage elongation at fracture is 25.9% and the ultimate-to-yield strength ratio is 1.50. The test results show that the ZG20SiMn cast steel has good ductility and strain hardening ability.

Table 1
Comparison of the actual and design specimen dimensions.

Parts of the joint	Measured sizes	Design sizes	Errors
The main pipe length (L)	806 mm	800 mm	0.75%
The main pipe diameter (D)	495 mm	500 mm	0.10%
The main pipe wall thickness (T)	39.5 mm	40 mm	1.25%
The branch pipes length (l)	1200 mm	1195 mm	0.42%
The branch pipes diameter (d)	345 mm	350 mm	1.71%
The branch pipes wall thickness (t)	34.6 mm	35 mm	1.14%
The chamfer (R_1)	994 mm	1000 mm	0.60%
The chamfer (R_2)	20.46 mm	20 mm	2.30%
The chamfer (R_3)	51.4 mm	50 mm	2.80%

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