Simulation Analysis and Experiment of Mechanical Performance of Bulge Formed Joint

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Abstract. In this paper, a new joint - bulge formed joint is proposed, which is designed for truss structure. Its mechanical performance is analyzed, and the finite element modeling and the simulation are carried on. The stress concentration theory is combined to obtain the stress concentration factor and compared with the direct intersecting joint, which shows superiority of bulge formed joint. On the basis of this, a test device is designed for stress test of the two kinds of joints. The results of the test verify the rationality of the result of the finite element simulation that the stress level of the bulge formed joint is small. Both the finite element simulation and the experiment show that the designed joint can improve the security of the joints.

Introduction

With the development of economy, the application of spatial structure is more and more extensive, the corresponding spatial structure joints have also developed by leaps and bounds, such as ball joints, intersecting joints and cast steel joints. The ball joints are mainly suitable for reticulated shells and truss structures[1].Although the bolted ball joints are structurally stable and easy to be manufactured, the assembly requirements are strict and require experienced personnel and there is a high risk for aerial work. Cast steel joints[2] can be overall cast, therefore, there are many advantages, for example, no welding stress concentration; good adaptability, design freedom; good shape, toughness and solderability. However, the requirements of material of the cast steel joints, which is mainly used low alloy steel, is very strict. On the one hand, C, S, P content must be controlled within the appropriate range, on the other hand, to add manganese (Mn) silicon (Si) chromium (Cr) and other elements is needed, which improve not only the strength of the material but also the plastic toughness and weldability of cast steel. So it costs lot and have long production cycle. The intersecting joints are also called simple joints, unstiffened joints, or direct welded joints[3]. The joints are mainly T-type (Y-type), K-type, X-type, YK-type, etc.; space joints are TT-type, XX-type, KK-type, KT-type and KX-type.

With the development of technology and the improvement of construction requirements, there have been new joints in the form of development[4,5]. The elliptical hollow section (EHS) has recently been used for construction due to its appearance and potential structural efficiency because of its two spindles. Hitachi has developed a drum-made pipe joint that reduces the stress at the joint to 55% of the traditional direct welding and significantly increases the life of the structure by eliminating the phenomenon that the stress at the junction of the welding joint affects the performance due to stress concentration. But it also has obvious shortcomings, the application in the manufacture of casting or hot forging joints are produced complex, time-consuming, and high cost.

In this paper, the structure and process are improved on the basis of Hitachi joint, and the bulge formed joint is proposed jointly with Shanghai Zhenhua Heavy Industries Co., Ltd (ZPMC). Although the new type of drum package use hot-rolled molding, the actual application of the joint only need to directly wrap in the corresponding chord, as shown in Figure 1. Thus, with uniform production of a set of hot-rolled mold based on different chord outer diameter the joint can be large-scale produced. Compared with the spherical joint the joint greatly reduces the weight of due to the plate hot-rolled molding .They are mostly thin-walled structures, which can increase the area to meet the number of connections, and insert the web into the "bulge formed" joint and then eliminate the force that is along the axis z(Z-force), greatly improve the security of the joint.
In this paper, the force characteristics of the intersecting joints and the bulge formed joints are compared, and the finite element models of both joints are established, and the numerical simulation experiments are carried out. Then the stress concentration factor is obtained based on the stress concentration theory. At the same time, the experimental study on the both joints is carried out, and the actual stress states of the joints are obtained. The results show that the stress concentration factor and the maximum stress of bulge formed joint are smaller, which is conform with the results of simulation. In other words, the security of the new joint is superior to the intersecting joint.

Analysis of Stress Concentration Coefficient

The connection strength is enhanced by lengthening the weld. At the same time, due to the application of bulge formed joints the anti-bending ability of the executive increasing the connection stiffness are improved.

At present, the research of the bulge formed joints is concentrated in the experimental research and numerical research, and the lack of the theoretical analysis of the ultimate bearing capacity of the bulge formed joints[6,7,8]. Due to the limitations of experimental research and numerical research, theoretical analysis is necessary.

Approximation of Welds

According to IIW, DNV specification, the weld has completed penetration form and part of the penetration form. This article uses the completed penetration form. For weld size the specification specifies that the minimum size at each point on the circumference of the intersecting line depends on the dihedral angle of the main chord and the web. So the size of the smallest weld at each point is different on the circumference of the intersecting line. Therefore, the satisfying of the requirements of modeling is very difficult. In this paper, the approximate modeling method is used, and the minimum size of the weld mainly meet the basic requirements. As for the comparison of stress concentration factor of different height and thickness of joints, the modeling method of this paper has certain reference value.

The Load is the Axial Tension or Pressure of the Web

When the both loads are the same, the stress concentration factor is the same. When the two web member respectively surfer a tension and pressure at the same time, the stress concentration factor is a little smaller. The following is the analysis of the load of tension or pressure at the same time.

According to the reference, when the length of the web member / diameter of the web member ≥ 8, the length of the main chord / the main chord diameter ≥ 16, the length of the main string, the length of the web member and the main string at both ends of the constraint form (all constraint or hinge constraint), the stress concentration factor can be not effected.

Stress Concentration Factor

The stress concentration factor is the ratio of the stress at the hot spot to the average stress on the web. For the direction of the hot spot stress, IIW defines that the principal stress at the weld toe is hot spot stress, but it is also said that the principal stress is usually perpendicular to the direction of the weld toe line. The AWS and API specifications dictate that the direction of the hot spot stress is perpendicular to the weld toe direction. This paper uses the latter to calculate.
Simulation Analysis and Its Results

Figure 2 is for the finite element (FE) model of joints and Figure 3 is the results of the simulation. As shown in Figure 3, the stress concentration of bulge formed joint is obviously smaller than the direct intersecting joint.

![Figure 2. The FE model.](image)

![Figure 3. The results of the simulation.](image)

The stress concentration factor at the intersecting line is the largest at the saddle point when the web is simultaneously pressed or pulled. The stress concentration factor of directly intersecting joint with 12 mm is 13.4. The stress concentration factor decreases with the increase of height and thickness. For the bulge formed joint, the effect of thickness is greater than the height.

For 16mm plate thickness, 150mm high bulge formed joints, the maximum stress concentration factor is 4.49, 33.6% of direct intersecting joints, and for 16mm plate thickness, 130mm high bulge formed joints is 4.9, 36.6% of direct intersecting joints, and for 14mm plate thickness, 130mm high bulge formed joints is 6.2, 46.3% of direct intersecting joints, and for 12mm plate thickness, 130mm high bulge formed joints is 8.1, 60.4% of the direct intersecting joints.

Experimental Research

The test is to explore the effect on the stress distribution, which caused by different load conditions of the strengthening plane K-type pipe joints and thickness. Experimental objects are bulge formed joints developed by Tongji University and ZPMC and traditional direct intersecting joints.

Fatigue Test Device

The invention is related to a fatigue test device for a new "bulge formed" joint, which consists of a reaction frame, a "bulge formed" joint, a hydraulic loading system, a cylinder connecting ear plate, a pin and a card board. It is characterized by the force structure, which is designed as a monolithic truss structure, and the new "bulge formed" joint is welded to the reaction frame. The whole test structure is like a small section of the truss structure that can be used to simulate the actual force test, and the test structure is simple, compact and easy to process; the reaction frame structure can ensure that the force of the test device is internal force and keeps inside the reaction frame, so the whole test device need not to install the base or platform, and can be free to lift; The hydraulic loading system can not only simulate the dynamic axial load of the truss webs and realize the switching of the pull and the pressure, but also realize the switching of dynamic load and static load on the joints. Fig.5 shows the detail of the test device.

![Figure 5. The fatigue test device.](image)

Specimen Specifications and Conditions

In order to obtain more comprehensive data, a number of test pieces and a variety of conditions are used. Table 1 shows specimen specifications.
Table 1. Specimen specification.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type</th>
<th>Thickness[mm]</th>
<th>Other parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>bulge formed joint</td>
<td>16</td>
<td>Main chord Φ426×16mm web member Φ156×16mm</td>
</tr>
<tr>
<td>2#</td>
<td>bulge formed joint</td>
<td>14</td>
<td>The angle between the main chord and the web member is 60°</td>
</tr>
<tr>
<td>3#</td>
<td>bulge formed joint</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>7#</td>
<td>direct intersecting joint</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Among them are Case 1:1#, 2# web members are loaded at the same time by the axial pressure of 9.82 tons, while Case 2:1#, 2# by axial tension 6.73 tons, and Case 3:1# web member is loaded by the axial pressure of 9.82 tons, while 2# by the axial tension 6.73 tons, and Case 4:1# by axial tension 6.75 tons, 2# by axial pressure 9.82 tons.

Results of the Experiment and Analysis

By analyzing acquired stress data, the maximum stress and its position under different conditions and the effect of the thickness of the bulge formed joint on the maximum stress can be obtained.

Maximum Stress in Each Case

Table 2 shows the maximum stress values of each joint under different cases.

Table 2. The maximum stress of each joint in different cases[MPa].

<table>
<thead>
<tr>
<th>Case</th>
<th>Joint</th>
<th>Bulge formed joint</th>
<th>Direct intersecting joint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>12 [mm]</td>
<td>14 [mm]</td>
</tr>
<tr>
<td>Case 1</td>
<td>72.4</td>
<td>78.9</td>
<td>74.4</td>
</tr>
<tr>
<td>Case 2</td>
<td>49.3</td>
<td>42</td>
<td>44.4</td>
</tr>
<tr>
<td>Case 3</td>
<td>35.2</td>
<td>23.7</td>
<td>23.5</td>
</tr>
<tr>
<td>Case 4</td>
<td>57</td>
<td>35.8</td>
<td>32.8</td>
</tr>
</tbody>
</table>

As shown in Table 2, the maximum stress of all bulge formed joints is less than that of the direct intersecting joints, except the 12 mm reinforced inner joint correspond to the intersecting joints, when the joints are subjected to a pressure and a pull load.

Comparing the maximum stress of 16 mm non-reinforced bulge formed joint and direct intersecting joint, the following conclusions are acquired: in Case 1, the maximum stress of the 16 mm without reinforcement bulge formed joint is 55% of the direct intersecting joint, while in Case 2 is 50%, and for Case 3 is 65%, and in Case 4 is 56% .

The Effect of Thickness on the Maximum Stress of Bulge Formed Joint

As shown in Table 3, as thickness of the plate increases, the maximum stress of the containment joint decreases.

Table 3. Comparison of maximum stress of bulge formed joint[MPa].

<table>
<thead>
<tr>
<th>Cases</th>
<th>12 [mm]</th>
<th>14 [mm]</th>
<th>Decrease of 14 mm relative 12 [mm]</th>
<th>16 [mm]</th>
<th>Decrease of 16 mm relative 14 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>72.4</td>
<td>78.9</td>
<td>-9.0%</td>
<td>74.4</td>
<td>5.7%</td>
</tr>
<tr>
<td>Case 2</td>
<td>49.3</td>
<td>42</td>
<td>14.8%</td>
<td>44.4</td>
<td>-5.7%</td>
</tr>
<tr>
<td>Case 3</td>
<td>35.2</td>
<td>23.7</td>
<td>32.7%</td>
<td>23.5</td>
<td>0.8%</td>
</tr>
<tr>
<td>Case 4</td>
<td>57</td>
<td>35.8</td>
<td>37.2%</td>
<td>32.8</td>
<td>8.4%</td>
</tr>
</tbody>
</table>

Conclusion

(1) With Q345 steel and forging molding, the cost of bulge formed joint is low.
(2) The nodal force is smooth and the fatigue stress concentration factor is small. The stress concentration on the joint is only 30% of the traditional joint.
(3) The welding line on the main chord are long, so the connection is firm.
(4) The length of the joint is up to 900 mm, which increases the rigidity of the entire truss.
The insertion of the web member into the bulge formed joint is connected to the plate, which avoids the Z-force that is generated by welding on the surface of the main chord in traditional joints.

Acknowledgement
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References
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