Experimental and Numerical Study on Impact Behavior of Welded Hollow Sphere Joint under Continuous Impact Load

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Abstract. In order to analyse the influence of continuous impact load and the stiffness of the welded hollow sphere joints on the impact resistance of the welded hollow sphere joints and verify the reliability of the generalized finite element software ANSYS/LS-DYNA precise modeling analysis of impact problems, two sets of the welded hollow sphere joints models with diameters of 80mm and 100mm were designed. The experimental results of three deformation stages (elastic, elastic-plastic and plastic deformation stages) in 18 working conditions of the two groups of models were analyzed. From the deformation mode, the acceleration and displacement of the sphere joint, the strain of the model member and the finite element simulation results, it is found that the test results and the finite element simulation are highly consistent. At the same time, the results show that the higher the stiffness of the welded hollow sphere joints, the better impact resistance of the joints. The continuity of the load has a great weakening effect on the impact resistance of the elastic-plastic and plastic deformation stages of the joints.

1. Introduction
In the 1950s, Germany began to use welded hollow spherical joints. Due to the high cost of welding in abroad, this kind of joint has been used less abroad in recent years. Since Professor Liu Xiliang first developed it in 1966, welded hollow spherical joints have been widely used in space structures. The domestic research on welded spherical joints mainly focuses on the non-linear finite element analysis of hollow spherical joints subjected to axial force, bending moment and their interaction. The ultimate bearing capacity of hollow spherical joints under different load combinations was analyzed [1-3]. The volume of the joint was simulated by a rigid arm long as the radius of the welded hollow sphere, and the stiffness of the joint was simulated by setting a spring element between the rigid arm and the bar. According to the stiffness regression formula of the welded spherical joint [4-5], the stiffness matrix of the beam element considering the stiffness of the rigid arm and the joint was derived. A more accurate formula for calculating the bending stiffness of joints was obtained by analyzing the bending stiffness of welded hollow spherical joints in pure bending condition [6]. Through dynamic analysis of refined model of single-layer reticulated spherical shell with welded spherical joints, it is concluded that the plastic development of joints will affect the dynamic stability of reticulated shells. When the wall thickness ratio of joints to members was greater than 1.5, the change of joint stiffness has less influence on the dynamic ultimate bearing capacity [7].
2. Test model

2.1 Test objective

- The numerical model of the welded hollow spherical joints under continuous impact load is verified by verifying the deformation mode, acceleration, strain of bar and dynamic response.
- Two typical failure modes (The spherical joint failure and member failure) and three typical deformation modes (The elasticity, elastic-plastic and plastic deformation modal) appearing in numerical analysis of welded hollow spherical joints are verified by two sets of model destructive impact tests.
- The reliability of welded hollow spherical joint is verified by comparing test results and numerical simulation results.

2.2 Loading device and test model

The adsorption equipment adopts two kinds of electromagnets: XD-Φ200R and XD-Φ300R. They were specially designed and customized in the factory. As shown in Figure 1, each electromagnet is equipped with a special electric cabinet. Through the measured, XD-Φ200R can hold up to 3 steel balls with diameter of 100mm and XD-Φ300R can hold up to 2 steel balls with diameter of 200mm at the same time. The lifting device is lifted by a laboratory-specific crane, and the maximum lifting height can reach 6m. The processing diagram of the model is shown in Figure 2.

![Electromagnet](image1.png)

(a) XD-Φ200R  (b) XD-Φ300R

Figure 1. Electromagnet

![Model Construction Drawing](image2.png)

Figure 2. Construction drawing of model

Two experimental models of welded hollow spherical joints with different diameters were made. The detailed parameters of the model are shown in Table 1. The welding hollow Sphere joints and bar are made of Q235 steel, their parameters are shown in Table 2. Welding is used between spherical joints and rods. E43 type electrode with strength of 160N/mm² is selected for manual welding to meet the requirements.

| Welded hollow sphere joint | Member |
|---------------------------|--------|
| Diameter (mm) | Diameter (mm) |
| Wall thickness (mm) | Wall thickness (mm) |
| Length (mm) | Number |

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Table 1. Model parameter.
Table 2. Parameters of material.

| Density (kg/m³) | Yield Strength (Mpa) | Elasticity modulus (Gpa) | Shear Strength (Mpa) | Shear Modulus (Mpa) | Poisson's ratio | C (s⁻¹) | P |
|----------------|---------------------|--------------------------|----------------------|---------------------|----------------|--------|---|
| 7850           | 235                 | 206                      | 125                  | 7.9×10⁴             | 0.3            | 40     | 5 |

In order to make better use of the camera to record the test phenomenon, we spray blue paint on the model and the support and white paint on the baseplate. When installing the baseplate is first installed, then a protective net is built, and finally the support is bolted to the baseplate. After the strain gauge is attached to the test model, the test model is fixed on the support. In order to prevent the impact of the impact on the paint on the floor, a 3cm thick black rubber pad was laid before the test. The overall test model is shown in Figure 3.

Figure 3. Test model

2.3 Measuring point arrangement and data acquisition

The data acquisition selects the DH5922 data acquisition instrument, and the maximum frequency of strain acquisition per channel can reach 1MHz. The symmetry of the test piece and the limitation of the channel of the collector, so the strain gauge of type BX120-2AA is only placed on the member bars of M₁ and M₂. Piezoelectric acceleration sensors of IA516 and IA520 are respectively arranged at the bottom of the spherical joint and on the member bar of M₃. The cable-stayed displacement meter CLMD2-AJ1A8P01XX is arranged at the bottom of the spherical joint. The arrangement of strain gauge, acceleration sensor and displacement meter are shown in Figure 4.

2.4 Loading scheme

There are two sets of models in this test. Each set of models tests 9 working conditions. When working conditions 1-5, the impact objects are 2 solid steel balls with a diameter of 100mm. When the working condition is 6-9, the impact objects are 2 solid steel balls with a diameter of 200mm. The first five working conditions of each model are elastic impact tests, and the last four conditions are elastic-plasticity and plastic impact tests. The loading scheme is shown in Table 3.
Table 3. Loading scheme.

| Condition number | Diameter of steel ball (mm) | Quality of steel ball (Kg) | Drop height (m) | Quantity of steel ball | Velocity (m/s) | Kinetic energy (J) |
|------------------|-----------------------------|-----------------------------|----------------|------------------------|---------------|-------------------|
| Model 1          |                             |                             |                |                        |               |                   |
| 1                | 100                         | 4.11                        | 1              | 2                      | 4.43          | 40.33             |
| 2                | 100                         | 4.11                        | 2              | 2                      | 6.26          | 80.53             |
| 3                | 100                         | 4.11                        | 3              | 2                      | 7.67          | 120.89            |
| 4                | 100                         | 4.11                        | 4              | 2                      | 8.85          | 160.95            |
| 5                | 100                         | 4.11                        | 5              | 2                      | 9.9           | 201.41            |
| 6                | 200                         | 32.87                       | 1              | 2                      | 4.43          | 322.54            |
| 7                | 200                         | 32.87                       | 2              | 2                      | 6.26          | 644.05            |
| 8                | 200                         | 32.87                       | 3              | 2                      | 7.67          | 966.85            |
| 9                | 200                         | 32.87                       | 4              | 2                      | 8.85          | 1287.23           |
| Model 2          |                             |                             |                |                        |               |                   |
| 1                | 100                         | 4.11                        | 1              | 2                      | 4.43          | 40.33             |
| 2                | 100                         | 4.11                        | 2              | 2                      | 6.26          | 80.53             |
| 3                | 100                         | 4.11                        | 3              | 2                      | 7.67          | 120.89            |
| 4                | 100                         | 4.11                        | 4              | 2                      | 8.85          | 160.95            |
| 5                | 100                         | 4.11                        | 5              | 2                      | 9.9           | 201.41            |
| 6                | 200                         | 32.87                       | 1              | 2                      | 4.43          | 322.54            |
| 7                | 200                         | 32.87                       | 2              | 2                      | 6.26          | 644.05            |
| 8                | 200                         | 32.87                       | 3              | 2                      | 7.67          | 966.85            |
| 9                | 200                         | 32.87                       | 4              | 2                      | 8.85          | 1287.23           |

3. Numerical model
The numerical simulation uses the general finite element software ANSYS/LS-DYNA. The welded hollow spherical joints and rods adopt the 4-node explicit structure thin shell element SHELL163. The impact object adopts the eight-node hexahedral solid element Solid 164, and the material model adopts the rigid body model Rigid Body. The contact type is Single Surface. The test material is Q235 steel, so the material model in the finite element is selected from the Piecewise Linear Plasticity Model which is suitable for steel and considers the strain rate effect of the material. The static yield strength of steel is based on Carbon Structural Steel GB/T 700-2006. The material parameters are shown in Table 2. The purpose of this experiment is to study the relevant performance of the welded hollow sphere joints under continuous impact load. In order to save computer memory and reduce the finite element calculation time, so the finite element modeling does not consider the support and the bottom plate, and the consolidation model for constraining all degrees of freedom is adopted at the model rod.
end. The finite element model is shown in Figure 5.

![Finite element model](image)

**Figure 5. Finite element model**

### 4. Experimental phenomena

There are two sets of test models for the entire impact test, and each set of models tests 9 conditions. There are two changes in impact energy:

- The impact energy is changed by changing the release height of the steel ball to change the impact velocity.
- The impact energy is changed by changing the mass of the impact steel ball.

There are three kinds of deformation modes of the welded hollow ball joints under continuous impact load. The deformation characteristics of the model under each mode are shown in Table 4. In the mode 3, the shear failure of the rod and the weld seam are not cracked, indicating the reliability of the weld joint connection of the welded hollow spherical joints. The results of the comparative test and the finite element simulation show a high degree of consistency between the two deformations (as shown in Figure 6). Under the same impact energy, the elastic stages of model 1 and model 2 have little difference and the elastic-plastic stages are quite different. In the destructive deformation stage, the first and second deformations are completely different. The welded hollow spherical joint of the model 1 weld is completely collapsed and the shearing failure of the rod is broken. The joint of the welded hollow spherical joint of the model 2 is largely collapsed, but the rod is not broken. Therefore, under the same impact energy, the stiffness of the welded hollow spherical joints is greater, and the impact resistance is greater.

| The deformed model | The deformation character of model                                                                 | Deformation state | Can continue to bear |
|--------------------|----------------------------------------------------------------------------------------------------|-------------------|----------------------|
| 1                  | There is no obvious displacement of the welded hollow sphere joints, and there is a phenomenon of paint falling and local depression at the impact point. | The elastic state | Yes                  |
|                    | There is obvious depression on the upper part of the welded hollow sphere joints, the sphere joint has obvious displacement, and there is a large area of paint falling off at the weld. | The elastic-plastic state | Yes                  |
| 2                  | The welded hollow sphere joints are seriously deformed, and the shearing damage occurs in the vicinity of the welded joint, but the weld has no cracking phenomenon. | The plastic state | No                   |

![Table 4. Deformation pattern.](image)
5. Analysis of test results

5.1 Acceleration analysis

The changes of model acceleration are shown in Figure 7. The default positive direction is vertical upward, and the impact direction is opposite to the positive direction. Therefore, the negative value in the figure is positive acceleration and the positive value is negative acceleration. In the elastic deformation stage, the change of acceleration is relatively complex, and the value of inverse acceleration is large. The finite element simulation value varies greatly with the increase of the impact height, and the test value changes more smoothly. In the elastic-plastic deformation stage, because the material is mainly plastic deformation and the elastic deformation is small, so the inverse acceleration is very small, and the test value is smaller than the finite element simulation value. The positive acceleration increases with the increase of impact height, the test value is greater than the finite element simulation value, and the maximum error is 0.4. The measured results of the model spherical joint and the rod acceleration are shown in Figures 7A₁ and A₂. The first peak occurs at the ball 1 impact sphere joint and the second peak occurs at the ball 2 impact sphere joint. The acceleration trend of the spherical joint and the rod is the same, and it is consistent with the finite element simulation in both the peak and the change trend, so the reliability of the finite element simulation is verified from the acceleration.
5.2 Displacement analysis
The displacement of spherical joints is shown in Figure 8. In the elastic deformation stage, there is almost no displacement for spherical joints; in the elastic-plastic deformation stage, the displacement changes small; and in the plastic deformation stage, the displacement changes greatly. The general trend shows that the measured value is greater than the finite element simulation value, model 1 is greater than model 2, the maximum displacement of model 1 is 0.18m, and the maximum displacement of model 2 is 0.15m. The displacement of the elastic-plastic deformation stage and the plastic deformation stage presents two descending stages. The first descending stage occurs after the steel ball 1 impacts the spherical joints, and the second descending stage occurs after the steel ball 2 impacts the spherical joints. In the plastic deformation stage, the displacement of the ball 2 impacting joints decreases more greatly, and the final displacement of the ball joints is the sum of the two descending sections. Through displacement analysis, it is verified that the greater the stiffness of welded hollow ball joints under the same impact load, the smaller the deformation after impact. In the elastic-plastic and plastic deformation stages, steel ball 2 plays a decisive role in the displacement of spherical joints.

5.3 Strain analysis
The strain of the member bar measured in the test is shown in Figure 9. The tensile strain is positive and the compressive strain is negative. In the elastic and elastic-plastic deformation stages, there is little difference between the strain changes of model 1 and model 2. In the plastic deformation stage, the strain difference between model 1 and model 2 is significantly different, and the maximum strain of model 1 is $2.53 \times 10^9$ times of model 2. According to the strain analysis of each stage of the test, it can be concluded that the greater the stiffness of the joint, the stronger the impact resistance.
6. Conclusion

Through continuous impact test on two sets of welded hollow spherical joint models with different diameters, and comparing the test results with the finite element software ANSYS/LS-DYNA simulation results, the following conclusions are drawn:

- The accuracy and reliability of the finite element software ANSYS/LS-DYNA dynamic response characteristics under simulated impact loads are verified by the high consistency between test and finite element simulation results.
- There are three kinds of deformation modes of the welded hollow spherical joints under continuous impact load, which are elastic deformation, elastic-plastic deformation and plastic deformation. The joint damage is greater than elasticity in elastic-plastic and plastic deformation.
- The welded joint of the welded hollow spherical joints and the bar is reliable. When the joint stiffness is large, the joint has good impact resistance.
- The continuity of the load has little effect on the elastic deformation of the welded hollow spherical joints, and has a great weakening effect on the impact resistance of the elastic-plastic and plastic deformation stages.

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