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Failure mechanism and practical load-carrying capacity calculation method of welded hollow spherical joints connected with circular steel tubes

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Abstract

The design standard of hollow spherical joint is nothing but "Technical specification for latticed shells" and "Specification for design and construction of space truss structures". For the hollow spherical joint with the same specification, design carrying capacity obtained from space truss specification is lower than that obtained from latticed shell. Especially when the material is Q345, calculation result will have 1 time difference. Hence, this article study deeply the failure mechanism of spherical joint under compression and the impact factor of load carrying capacity.

This article studies the content mentioned above in 4 ways: finite element analysis, significance analysis of influencing parameter, theoretical analysis and experimental analysis. Based on the linear hardening elastic-perfectly plastic model and the Mises yield criterion, a finite element model for the analysis of these joints is established, in which the effect of geometric nonlinearity is taken into account. The whole loading course of 68 joints is calculated by the use of arc-length method. This paper investigates systematically the structural behavior , load-carrying capacity and failure mechanism of joints, and determines the judgment criteria of ultimate bearing capacity. My study reveals that: for the compressed spherical joint that satisfy construction requirement of the last 2 technical specification, the failure mode is neither strength failure of material nor stability failure of spherical structure. It's due to plastic expansion of material that cyclic plastic hinge is developed and cause the load carrying capacity of hollow spherical joint to lose. By the further analysis, the concept of failure key section is formed, in which shear is dominant stress and as $1/\sqrt{3}$ times as failure Mises stress.

According to the ultimate load-carrying capacity obtained from finite element analysis, data point is designed based on orthogonal method, utilizing F-inspection from mathematical statistics to perform multi-parameter and single-factor significance analysis of compressive load capacity. The result indicates that yield strength of spherical material fy are the critical factor that influence the load carrying capacity of hollow spherical joint, as well as wall thickness t, outer diameter of sphere D and outer diameter of steel tube d.

Comparatively destructive experiments on 8 typical full-scale joints made from two different graded material, Q235B and Q345B, were conducted to understand directly the structural behavior and the collapse mechanism of the joint, and also to validate the finite element analysis and parameter study. Finally, the simplified theoretical solution is also derived for the loading-carrying capacity of the joint based on the punching shear failure model, and the basic form for the design equation is obtained. By applying the results from the simplified theoretical solution, finite element analysis and experimental study, and utilizing the theory of mathematic statistics and regression analysis, the practical calculation method is established for the load-carrying capacity of the joints subjected to axial compressive forces. By the check of large amount of experiment data, the calculation result obtained from this formula is consistent with experiment result, and the practical formula has safety reserve meeting the regulation in national codes. The achievements from this study can be applied for direct design , and also provide a reference for the revision of relevant design codes.

Keywords: Welded hollow spherical joint, Circular steel tube, Nonlinear finite element analysis, Destructive mechanism, Load-carrying capacity, Influencing parameter, Experimental research, Practical calculation method

1. Introduction

From 1965 to now, lots of scholars have made much of work on load-carrying capacity of hollow spherical joints under compressive load, and determined that joint connected with many members can be simplified into joint with single member. Some scholars researched effects of weld on capacity, and dynamic behaviour. Tests on joint were all limited by material graded Q235. The number of experiment of joint mad from Q345 was very small. Achievements about it developed into the "Technical specification for latticed shells [1]" and "Specification for design and construction of space truss structures [2]".

With the increasing appearance of large span spatial structure, large amount of welded hollow spherical joints has been applied to other structures in addition to latticed shell and space truss, but the design standard of hollow spherical joint is nothing but "Technical specification for latticed shells" and "Specification for design and construction of space truss structures". For the failure mechanism of welded hollow spherical joint under compression, which have different understand. Technical specification for latticed shells consider it as stability failure, load-carrying capacity has nothing to do with the yield strength of spherical material; whereas, technical specification for latticed shells consider it as strength failure, yield strength of spherical material affects load-carrying capacity directly. For the hollow spherical joint with the same specification, design carrying capacity

obtained from space truss specification is lower than that obtained from latticed shell. Especially when the material is Q345, calculation result will have 1 time difference, which will affect seriously engineer's judgment in the design of hollow spherical joint.

Hence, this article study deeply the failure mechanism of spherical joint under compression and the impact factor of load carrying capacity to find out the failure mechanism and determine the influence of yield strength of material. By the analysis of influence factors, key factors effecting joint load-bearing capacity are found out. Furthermore the paper carried out comparatively destructive test to 8 joints made from material graded Q235 and Q345, which is first time on the way of the research about joint load capacity.

2. Finite element analysis

2.1 Finite element model

The proposed finite element model, 1/4 sphere welded to circular steel tube, subjected to uniaxial force, has been simulated with 8-node hexahedron solid element Solid45 [3] [4] [5]. The refined meshes have been applied to the connection region, as shown in Figure 2-1.
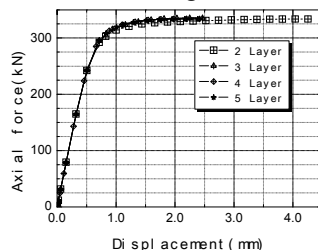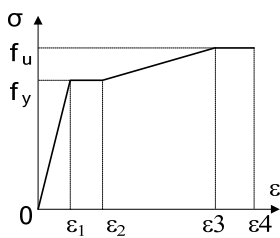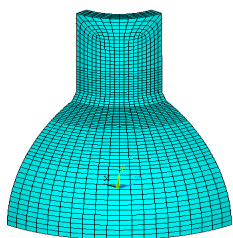

| Fig.2-1 Finite element grid | Fig.2-2 Stress-strain curve | Fig.2-3 Element grid accuracy |

The ideal elastic-linearly hardening stress - strain model and the isotropic hardening rules for Von-Mises yield stress, as well as the non-linear geometric effects have been taken into account through the arc-length method to get the full loading history. Stress - strain relationship curves [6] [7] shown in Figure 2-2. For Q235 steel, fy = 235MPa, fu = 375MPa, ε_1 = 0.114%, ε_2 = 2%, ε_3 = 20%, ε_4 = 25%; and for Q345 steel, then fy = 345MPa, fu = 510MPa, ε_1= 0.168%, the rest of the corresponding strain are the same as steel Q235.

It can be shown in Figure 2-3 that the results of 4-layer-grid model show great promise in contrast to refiner models. Compared to the literature's results [8] [9], the average deviation of the proposed finite element model's, which is 3.1% in compression, indicate acceptable accuracy in respect to the same material constitutive model and loading conditions.

2.2 The criteria of ultimate capacity

In the view of material damages, the ultimate capacity is the loading corresponding to the steel ultimate strain 0.15; in the view of joints stability, the ultimate state is the first extreme point on the load-deformation curve. Both of the failure patterns constitute the criteria of ultimate load-carring capacity.

2.3 Joints' failure mechanism in compression

68 groups of joint experiments have been analyzed through the proposed finite element model. According to the current design specifications and practice, the geometric parameters of hollow spherical joints are as follows: 300/400 mm in diameter, the ratio of diameter to wall thickness is: $25 \leq D / t \leq 45$, the ratio of diameter to tube is: $2.4 \leq D / d \leq 3.0$. To investigate the ultimate load-carrying capacity of the spherical joints, the connection strength of welds have been designed stronger than the strength of joints.

The development of internal force and procedure of destruction can be illustrated through the example of spherical joint D300x8 (Q235B) with tube d102x14. The stress diagram corresponding to ultimate loading has been marked by figures, the other curves show the stress distribution in respect to yield loading. The spherical joints undergo 3 stages subjected to axial compression load: elastic stage, plastic stage, destruction stage. As can been seen in Figure 2-4, not only membrane stress, but also a high level of bending stress undergo as the axial loading increasing. The connection region sustained the most severe stress when the initial yielding occurrences at the outer surface; with the increasing of loading, the yielding develops along the thickness of the joint; the joint load-carrying capacity drops sharply after the tensile stress of inner surface reach the yield stress. The extreme deformation could be observed at this stage. Due to the post-yield stain hardening, the re-increasing load-carrying capacity has been captured in the finite element analysis, as well as the experimental results.

As the simulation is shown the relationship of the ultimate load-carrying capacity with the stress condition, due to the material nonlinearity, the occurrence of the joints destruction starts at the same time when the full section plasticity has been formed at the joint-tube connection. Therefore, the failure mechanism of spherical joints in axial compression is strength failure in respect to large plastic deformation which induced through the development of plasticity.
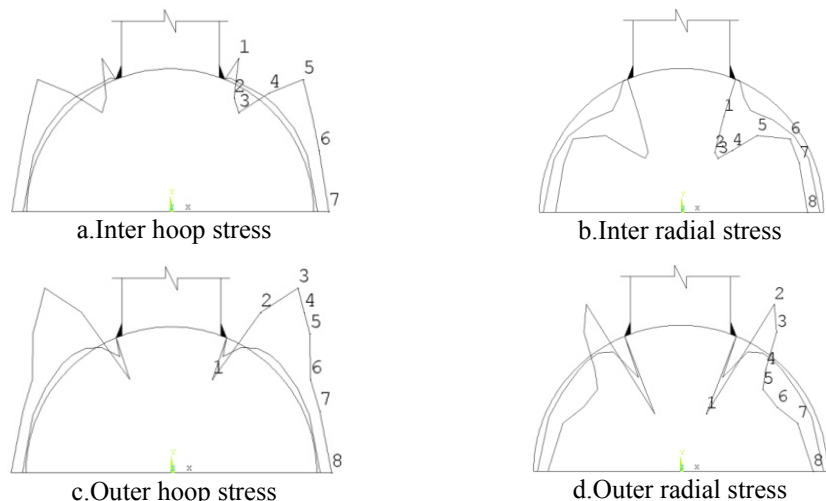
a.Inter hoop stress

b.Inter radial stress

c.Outer hoop stress

d.Outer radial stress

Figure2-4 Stress Contour of D300 Sphere of Axial Compression

Also can be seen in Figure 2-5, the maximum stress is lower than the ultimate strength of material, which also shows the failure model of joints is not material's strength failure.

Based on the distribution of the membrane and Mises stress, the maximum value which occurs around the vicinity of node 3, known as theoretical damage surface, controls the joint capacity. However, according to the development of the internal stress, the weld toe of the connection region, known as actual damage surface where the material undergoes the maximum initial stress, should also be given more attention and be. As shown in Figure 2-6, the development of Mises and Sxy stress share the same track at weld toe of the connection region, the difference in magnitude is $\sqrt{3}$. The punching effect of axial load can be expressed through the physical concept.
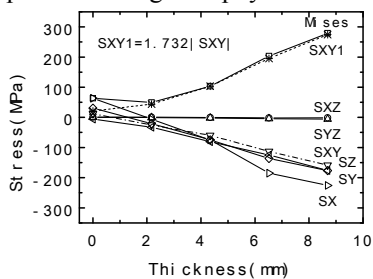
a.Yield load on 1# section
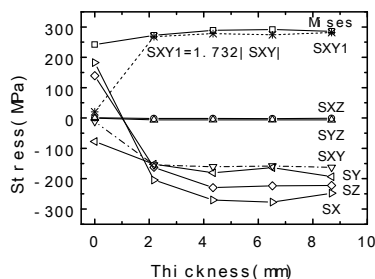
a.Ultimate load on 1# section

Figure2-5 Key Section Stress of Axial Compressive Sphere

3. Influential parametric analysis

3.1 Orthogonal analysis model

It's necessary to study influential parameters that decide compressive capacity of welded hollow spherical joint. The core issue is whether under certain construction requirements, yield strength of steel effect significantly the load-carrying capacity of spherical joint. Orthogonal experiment is a mathematical method that study and deal with several influential parameters and then can manage experiment scientifically according to orthogonal array, then perform statistic analysis and calculation of the experiment result based on the characteristic of orthogonal array and finally obtain reliable conclusion.

According to the achievements made by former researcher, several parameters sphere outer diameter D, sphere wall thickness t, yield strength of sphere steel fy, outer diameter of steel tube d are investigated as influential parameter. Utilizing orthogonal array L9(3^4) to conduct direct analysis and significance analysis regarding load-carrying capacity of spherical joint at ultimate stage. The constitutive relationship of steel material is ideal elastic-plastic material.

3.2 Significance analysis of parameter

Geometric parameter of calculation mode is shown in Table 2-1. Orthogonal array for ultimate compressive capacity is shown in Table 2-2. Variance analysis is shown in Table 2-3.

Table2-5 Geometric parameter of mode

No.	D	t	d	td	fy
1	300	8	102	14	235
2	300	8	108	14	345
3	300	8	114	14	390
4	300	10	102	14	345
5	300	10	108	14	390
6	300	10	114	14	235
7	300	12	102	14	390
8	300	12	108	14	235
9	300	12	114	14	345

Table2-3 Variance analysis

Variance	Sum of deviance	Degree	Sum of mean	F-ratio	Significance
t	168299	2	84149	28.37	significant
d	6824	2	3412	1.15	not
f_y	174730	2	87365	29.45	significant
e	5932	2	2966		

$\alpha=0.10$, $F_{0.90}(2,2)=9.00$

Table2-2 Orthogonal analysis of compressive load-carrying capacity

Influential parameter		t	d	f_y	blank	Ultimate capacity N_i(kN)	
Low	Line No.	1	2	3	4	N_i	N_i^2
1		1	1	1	1	376.87	142028.98
2		1	2	2	2	584.82	342008.90
3		1	3	3	3	703.12	494382.65
4		2	1	2	3	716.05	512724.61

5	2	2	3	1	870.12	757115.99
6	2	3	1	2	564.58	318750.62
7	3	1	3	2	1008.66	1017400.71
8	3	2	1	3	650.05	422570.52
9	3	3	2	1	1010.79	1021705.04
Sum of 1 levelⅠ	1664.81	2101.6	1591.5	2257.8	6485.07	
Sum of 2 levelⅡ	2150.75	2105.0	2311.7	2158.1	5028688.01	G=6485.07
Sum of 3 levelⅢ	2669.51	2278.5	2581.9	2069.2		$\sum_{i=1}^{9}N_i^2 = 5028688.01$
SA$_i$	168298.6	6824.0	174730.	5932.4		
Se$_i$	5932.41	5932.4	5932.4			

SAi:Sum of square of condition deviance Sei: Sum of square of condition deviance

From the variance analysis of Table2-3, F-testing value of fy and t is above the critical value under 10% confidence level which means yield strength fy and Wall thickness t is very significant to load-carrying capacity, while the influence of outer diameter of steel tube d is insignificant. The failure mechanism of sphere joint is the gradually plastic expansion of sphere until load-carrying capacity to lose. Hence, failure is relevant to the extent of plastic expansion of sphere, that is to say failure has something to do with wall thickness of sphere and yield strength of material. But outer diameter of steel tube affect directly the initial plastic level of sphere, since the bigger the tube diameter, the lower of stress level along the perimeter cross-section of sphere.

We can see clearly that compressive capacity is in proportion to material strength, while calculating in case of just changing joint's material grade.

4. Test analysis

4.1 Test overview
According to the current design specifications and practice, the geometric parameters of hollow spherical joints meets the construction requirement. Table 4-1 shows the parameters of the 8 samples with respect to 2 different value of diameter made from Q235 and Q345:

Table 4-1 Parameter of test specimen

No.	Sphere specification	Circular tube	Material grade	Load type
Q2D3C	D300x8	d102x14	Q235B	compress
Q3D3C	D300x8	d102x14	Q345B	compress
Q2D4C	D400x14	d150x22	Q235B	compress

| Q3D4C | D400x14 | d150x22 | Q345B | compress |

To prevent the failure pattern from insufficient strength capacity of steel tubes, all of the steel tubes are 6 ~ 8mm thicker than the spherical ball's, 2.0 times the sphere diameter in length[11] [12]. Figure 4-1 and Figure 4-2 suggest the layout of the test. There are 20 strain rosette on the sphere and weld, and 12 strain gauge on the tube. Four displacement transducer are laied on the end of joint member, the mean number of which is axial displacement.

4.2 Material test
Material mechanical properties of hollow sphere have to be tested in order to use in finite element calculation before joint test. The results of tension test based on national standards shown in Table 4-2.

Table 4-2 Mechanical properties of hollow spheres

Item	Data	Q2t8	Q3t8	Q2t14	Q3t14
Elastic modulus （N/mm2）	Mean value	2.065E+05	2.075E+05	2.187E+05	2.235E+05
	Variation Coefficient	0.191	0.062	0.025	0.047
Yield strength （N/mm2）	Mean value	290.056	362.687	298.645	364.632
	Variation Coefficient	0.033	0.004	0.015	0.032

Table 4-2 indicates that the yield strength of Q235 is about 1.25 times the recommended value in codes; while the yield strength of Q345 is about 1.05 times the one. The Elastic modulus is closer to the suggested values for thinner plate.
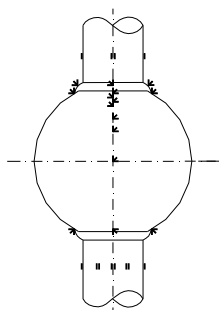

Fig.4-1 strain gauge plan

Figure4-2 Test photo

Fig. 4-3 Central failure modes

Fig. 4-4 Torsional failure modes

4.3 Test results and comparative analysis

Subjected to the increasing axial load, the Specimen undergoes three stages: elastic stage, plastic stage, destruction stage. In the load-deformation curve, the linear portion indicates the stable elastic stage; during the elastic-plastic stage, the slowly reducing gradient of the curve shows the development of plasticity; compared to the sable portion of plastic stage, rapid growth in displacement has been observed during the test. Even without the help of instrument, the unstable plastic deformation can be addressed during the destruction stage.

The failure patterns of total 8 specimen have been classified into 2 categories: one is central deflection, which the spherical joint sustain a unrecoverable center deflection, shown in Figure 4-3; the other is spherical torsional deflection, which the central deflection accompanied by the tubes rotation along the central axis, shown in Figure 4-4.

Table 4-3 Comparison of FEA with experimental results

No.	Test result				Document data (kN)	FEA result			
	Yield capacity	Dis.	Ultimate capacity	Dis.		Yield capacity	Dis.	Ultimate capacity	Dis.
Q2D3C1	198.75	0.59	461.44	3.23	460.00	239.38	0.42	463.83	1.76
Q2D3C2	182.38	0.50	483.25	2.59					
Q3D3C1	473.79	0.96	570.99	3.30	/	294.00	0.95	576.68	2.15
Q3D3C2	398.86	0.54	579.74	3.10					
Q2D4C1	847.71	0.77	1601.3	6.15	1196.40	794.39	0.69	1289.66	3.21
Q2D4C2	1037.5	1.13	1511.9	5.70					
Q3D4C1	1377.7	1.43	1850.2	7.63	/	799.44	0.72	1571.79	4.16
Q3D4C2	1097.7	2.88	1708.5	9.57					

Unit : kN、mm

The comparison of the results of experiment and the finite element analysis, as well as the load-deformation curves have been shown in table 4-3 and Figure 4-5.

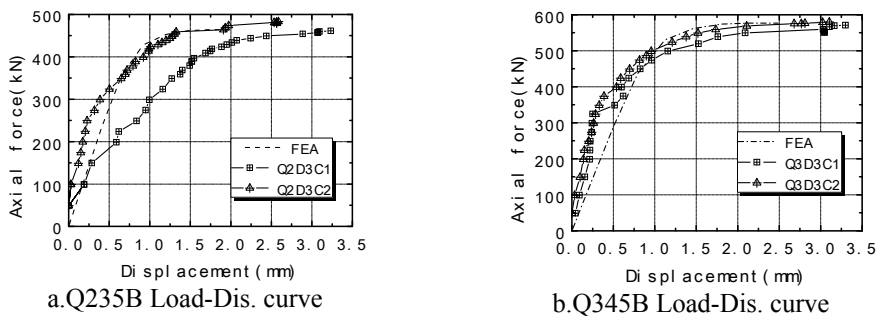a.Q235B Load-Dis. curve   b.Q345B Load-Dis. curve

Figure 4-5 D300 load - displacement curve

The comparison shows great consistent between the FEA results and the experimental results. The predicated curves are consistent to the experimental results, as well as the literature. The proposed model can be used for practical analysis.

5. Practical Design Method

5.1 Formula of compression capacity

The proposed FEA model results indicate that control stress at the weld toe of the connection of the weld hollow spherical joints is shear stress. In consequence, the internal force on the control surface could be simplified as vertical shear stress component. According to the equation of equilibrium, the joint loading capacity is equal to the vertical shear stress on the control surface. Furthermore, the fully section plasticity as well as the strain hardening effect increase the shear stress to τ_u, as shown in Figure 2-5, the simplified calculation model for spherical joint under axial compression limit state has been shown in Figure 5-1.

Based on the equilibrium condition, a simplified expression of the ultimate capacity

$$P_u = \pi\delta(d + 2w)\tau_u \tag{1}$$

5.2 Practical design formula

Assume $\tau_u = \mu f$, μ is a parameter depends on the geometry of the spherical joint, and its expression can be solved through the statistical formulas[13] [14]. Therefore, the ultimate capacity formula for compression spherical joint as follows:

$$P_u = \mu\pi t d f \tag{2}$$

The discussion on the determination of coefficient μ is as following: First, μ is related with many parameters, such as geometric parameters of joint, properties of spherical material, various variable index leads to various; Secondly, the comparison to current code recommend formula is required; Finally, previous studies showed that compression capacity and steel properties are related. Therefore, taking td/D^2 as variable, inspect the relationship of $Puc/\pi tdf$ and td/D^2, as well as the statistical analysis. The linear relationship between $Puc / \pi tdf$ and $td/D2$ is shown in Figure 5-2, the linear correlation coefficient $\gamma = 0.291$, the correlation threshold $\gamma_{0.05} = 0.250$ (degrees of freedom 60) at the confidence level of 0.05.Extracting the slope values from linear regression analysis forms the coefficient b in the formula of $a + b\ td/D^2$; in accordance with the requirement of literature [10], which the test ultimate capacity should be greater than 1.6 times the design ultimate capacity, the coefficient a is determined, the final recommended ultimate capacity formula for compression spherical joint as follows:
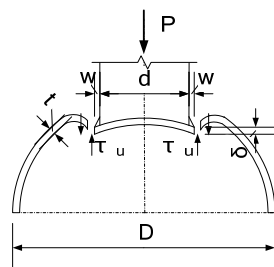
Figure5-1 Simplified model

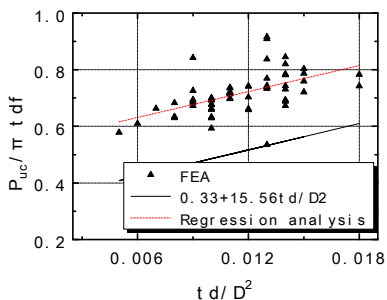$$P_c = (0.33 + 15.56\frac{td}{D^2})\pi tdf \tag{3}$$
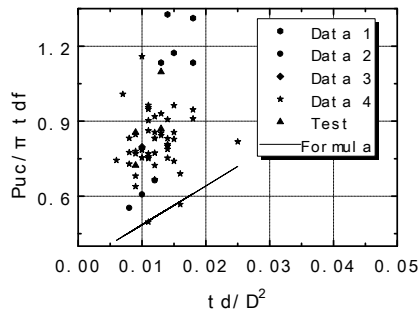

Figure5-2 Regression analysis

Figure5-3 Regression formula check

Table5-1 Calculation formula check

No.	P_{uc}	$P_{uc}/(3)$	$P_{uc}/[2]$	$P_{uc}/[1]$
Q2D3C	471.4	1.82	1.732	1.588
Q3D3C	574.6	1.538	1.464	1.936
Q2D4C	1556.6	2.062	2.135	2.245
Q3D4C	1779.3	1.635	1.693	2.566

The proposed model has been compared to literatures[10], the results are shown in Figure 5-3. As the figure shown, out of the total 63 samples, the 61 samples' values are greater than the values which is calculated from the recommended formula. Table 4-1 indicates the proposed formula is reliable and applicable.

6. Conclusion

1) It is correct and available for hollow shperical joint that the ideal elastic-linearly hardening stress - strain model and the isotropic hardening rules for Von-Mises yield stress, as well as the non-linear geometric effects have been taken into account through the arc-length method to get the full loading history.

2) For the compressed spherical joint that satisfy construction requirement of the last 2 technical specification, the failure mode is neither strength failure of material nor stability failure of spherical structure. It's due to plastic expansion of material that cyclic plastic hinge is developed and cause the load carrying capacity of hollow spherical joint to lose.

3) The concept of failure key section is formed, in which shear is dominant stress and as $1/\sqrt{3}$ times as failure Mises stress.

4) Yield strength of spherical material fy are the critical factor that influence directly the load carrying capacity of hollow spherical joint, as well as wall thickness t, outer diameter of sphere D and outer diameter of steel tube d.

5) Comparatively destructive experiments validate the collapse mechanism of the joint, and the finite element analysis and parameter study.

6) The practical calculation method is established for the load-carrying capacity of the joints subjected to axial compressive forces. The calculation result obtained from this formula is consistent with experiment result, and the practical formula has safety reserve meeting the regulation in national codes.

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