

Fire performances of space grid structures

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Abstract

Fire performances of six welded hollow spherical joints are experimentally investigated and numerically simulated with the thermal parameters specified in the EUROCODE 3 and the standard fire temperature-time curve ISO 834. The temperature fields, the displacement properties and the stress characteristics of these joints are studied. Based on the nonlinear finite element analysis of the space grid structure under fire, the temperature field characteristic and the behavior of the structure under fire are discussed. Finally, several rules on the practical fire-resistant ability of the space grid structure are concluded, and some suggestions on the fire-resistant design of the structure are proposed as well.

Keywords: fire, performance, space grid structure.

1. Introduction

In recent decades, a large number of public buildings with space grid structures, such as airport terminal, gymnasium and museum, have been built in many cities of the world. Most of these structures are constructed by steel members and joints. However, the steel members share poor fire-resistant performances. The steel members can not bear any loads once their temperatures reach 600 °C. In general, the temperature field of fire is about 800 °C ~ 1000 °C, so these structures will be damaged or even collapse under fire. Although the space grid structures have been widely used, researches on their fire behaviors lag behind their developments. In the past decades, the fire-resistant researches of steel structures mainly focused on the properties of steel under fire, the temperature fields of member and space, and the fire-resistant properties of members and frame structures, etc (Li *et al.* [4]). To learn more information about the fire performances of the space grid structures, the experiments and numerical simulations on the fire performances of the welded hollow

spherical joints that are normally used in these structures were firstly performed. Then the nonlinear finite element analysis on one of these structures under fire was discussed in the present paper.

2. Experimental investigation on properties of the welded hollow spherical joints under fire

2.1. Finite element model and test specimen

Six welded hollow spherical joints were designed to study their properties under fire, whose heights were all 1570 mm. The sizes of these joints are shown in Figure 6 and 7, in which D and t_1 represent the diameter and the thickness of the welded hollow spheres, d and t_2 denote the external diameter and the thickness of the welded steel pipes, respectively.

The finite element model of thermal-mechanical coupling analysis was built by the finite element software ABAQUS, and the model is shown in Figure 1 (a). The thermal elongation, the thermal conductivity, the specific heat and the stress-strain relationship allowing for strain-hardening of steel, which were varied with the environmental temperature, were chosen based on the EUROCODE 3. The Poisson ratio, the elastic modulus, and the density of steel were taken as 0.3, 206000 MPa, and 7850Kg/m³, respectively. The geometric and material nonlinear of steel was considered.

Several tests on the fire properties of the welded hollow spherical joints under axial pressure were carried out in the Structural Engineering Test Center of Qingdao Technological University. Figure 1 (b) displays the test specimen. The standard fire temperature-time curve ISO 834, which have been widely used in the previous studies, are adopted in this work. The equation of the curve is expressed as (International Standard ISO 834 [1])

$$T_g = 345 \log_{10}(8t + 1) + T_g(0) \quad (1)$$

where T_g is the temperature of the air, $T_g(0)$ the room temperature (20°C), and t the time.

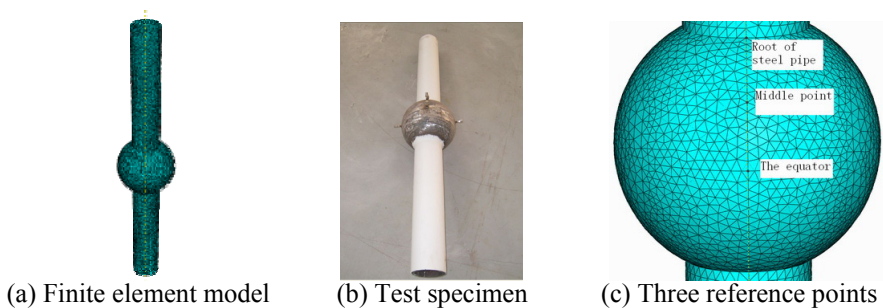
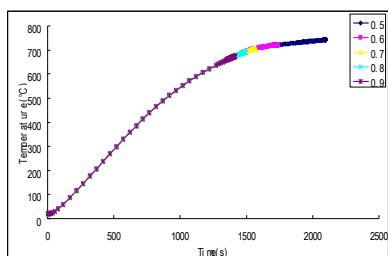


Figure 1: The welded hollow spherical joint and its numerical model

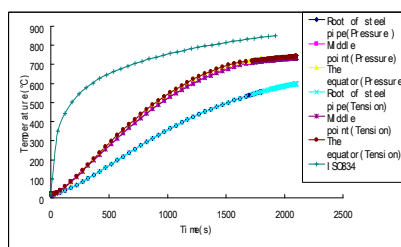
2.2. Numerical simulation results and comparison with the experimental results

Firstly, the numerical simulations were performed to investigate the properties of the welded hollow spherical joints under fire. Six joints were simulated under axial pressure or tension of five different load ratios which are the ratios of the real bearing loads and the design loads, respectively. For each joint, three reference points shown in Figure 1 (c) were selected to analyze its fire performances. In this paper, only the results of the first joint listed in the Figure 6 and 7 are shown.

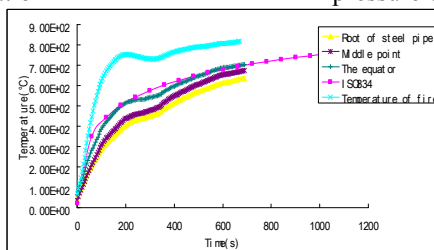
Due to the same temperature field adopted in the simulation of the same joint, the temperature curves under different load ratios are coincident, however the ultimate fire-resistant durations of these curves are different. The smaller the load ratio is, the longer the duration is, which can be seen from Figure 2 (a).



(a) Temperature curves of the equator under different load ratio



(b) Temperature curves under axial pressure or tension



(c) Experimental temperature curves of three reference points

Figure 2: Temperature curves of three reference points on the welded hollow spherical joint under axial pressure, the load ratio is 0.5

From Figure 2 (b), the temperature curves of the three reference points, which is shown in Figure 1 (c), are different obviously from the curve ISO 834 in the beginning, while their differences become smaller and smaller with time. The temperature of the equator is the highest, and the temperature of the middle point is about 20°C lower than that of the equator. The temperature at the root of the steel pipe is about 170°C lower than that of the equator. The ultimate fire-resistant duration of the joint under axial tension is longer than that under axial pressure, because the ultimate tensile bearing capacity of the joint is greater than its ultimate compressive bearing capacity. The smaller the load ratio is, the longer the duration is.

The test of the fire performances for the first joint listed in the Figure 6 and 7 is shown in Figure 3, and the temperature plot of this test is shown in Figure 2 (c). The temperature of the fire is higher than ISO 834 because the control of the fire is difficult. Considering that the fire is put on the joint directly in the experiment, the temperatures of the reference points are higher than those calculated in the simulation, in which the heat is transmitted to the joint by the air.



(a) Fire-Resistant test equipment (b) Joint before the test (c) Joint after the test
 Figure 3: Fire performance test on the welded hollow spherical joint

Figure 4 (a) and (b) illustrate the experimental and the simulated displacements of the joint. It can be seen that the displacements decrease at first, and increase with the rising of the temperature, which can be explained as follows. In the beginning, the displacement is mainly resulted from the thermal expansion of the joint. With the increase of the temperature, the yield strength and the stiffness decrease, and the displacement becomes bigger and bigger until the failure of the joint. The final displacement is the superposition of the displacements due to the thermal expansion of the joint, steel softening and the dead load. In the experiment and the simulation, the root of the steel pipe fails at first, therefore, it is the weakest part of the joint. The failure modes are shown in Figure 5. From the experiment, it is found that there is no crack in the specimen as the temperature increasing, while the crack occurs when the temperature is decreasing because the stress of the joint is redistributed, and the crack is shown in Figure 5 (c). The results of the other joints are similar (not shown in this paper).

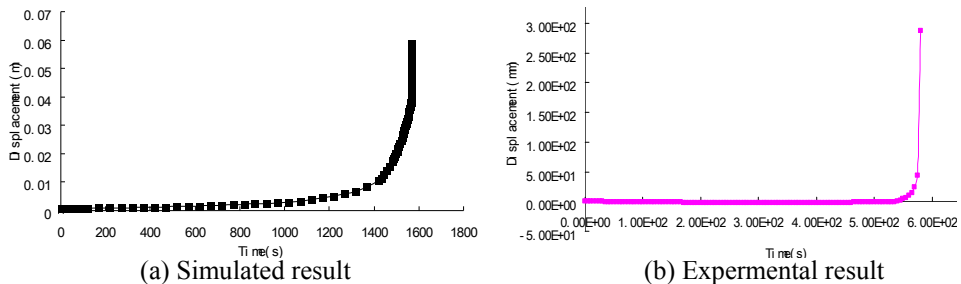


Figure 4: Displacements of the first joint



Figure 5: Failure modes of the first joint

The ultimate fire-resistant durations of the joints under axial pressure or tension are shown in Figure 6 and 7, respectively. They indicate that the ultimate fire-resistant durations of the joints can be prolonged through decreasing the load ratio or increasing the thickness of the welded steel pipe. The reason is that the transmission of the heat on this condition becomes faster, thus, more heat is transmitted. However, the method of increasing the thickness can increase the consumption of steel. Increasing the diameter or the thickness of the welded hollow sphere or the external diameter of the welded steel pipe can enhance the load-carrying capacity of the joint. However, these methods can not always prolong the duration. Although the higher yield strength of steel will increase the load-carrying capacity of the joint, the duration decreases.

Joint (mm)				Load ratio										Yield strength (MPa)
D	t ₁	d	t ₂	0.5		0.6		0.7		0.8		0.9		
				t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	
280	10	133	8	1798	725	1625	711	1494	692	1431	678	1343	657	235
280	10	133	12	1951	733	1687	716	1574	704	1485	687	1361	658	
280	12	133	12	1848	716	1692	700	1587	679	1502	659	1427	641	
300	10	133	8	1901	732	1582	709	1482	693	1405	676	1342	660	
300	10	140	8	1801	726	1623	712	1499	695	1410	676	1372	666	
280	10	133	8	1716	719	1541	702	1452	683	1378	665	1292	643	345

Figure 6: Ultimate fire-resistant durations of the welded hollow spherical joints under axial pressure

Joint (mm)				Load ratio										Yield strength (MPa)
D	t ₁	d	t ₂	0.5		0.6		0.7		0.8		0.9		
				t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	t (s)	T (°C)	
280	10	133	8	2098	742	1737	721	1567	705	1489	691	1414	674	235
280	10	133	12	2221	749	1842	727	1605	708	1550	700	1456	681	
280	12	133	12	2224	739	1830	715	1691	700	1617	685	1556	672	
300	10	133	8	2226	752	1820	727	1599	710	1503	697	1439	684	
300	10	140	8	2065	741	1753	722	1562	706	1480	691	1429	680	
280	10	133	8	2070	741	1706	718	1549	703	1474	688	1391	669	

Figure 7: Ultimate fire-resistant durations of the welded hollow spherical joints under axial tension

3. Performances of space grid structure under fire

3.1. Parameters of geometric model

To learn more information about the fire performances of space grid structures, the nonlinear finite element analysis was performed for one of these structures (shown in Figure 8). The steel roof system supported on four edges is the square pyramid space grids structure, and its thickness is 2.4 m. The building height is 9 m, and the yield strength of steel 235 MPa. All steel members of the structure are seamless steel pipes.

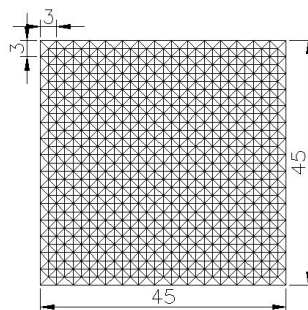


Figure 8: Plan of the structure

3.2. Fire model

In the present paper, five fire locations, which are assumed to be circular, are designed. The areas, coordinates and radius of the fire are shown in Figure 9. The thermal releasing power

of the fire is 25MW, and the equation of the temperature field considering space factors is written as follows (Li *et al.* [3]):

$$T_{(x,z,t)} - T_g(0) = T_z [1 - 0.8 \exp(-\beta t) - 0.2 \exp(-0.1\beta t)] \times [\eta + (1 - \eta) \exp(-\frac{x-b}{\mu})]$$

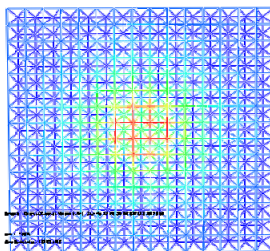
(2)

Model	Model 1	Model 2	Model 3	Model 4	Model 5
Area (m ²)	50	50	50	100	250
Radius (m)	3.99	3.99	3.99	5.643	8.922
(x,y)	22.5,22.5	13,22.5	4,22.5	22.5,22.5	22.5,22.5

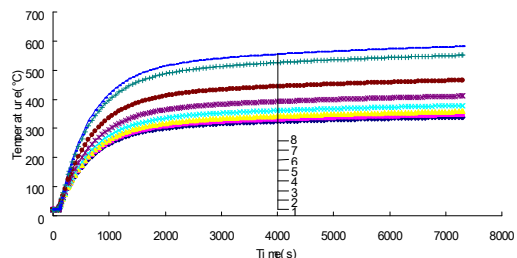
Figure 9: Fire locations in the space grid structure

3.3. Numerical analysis results

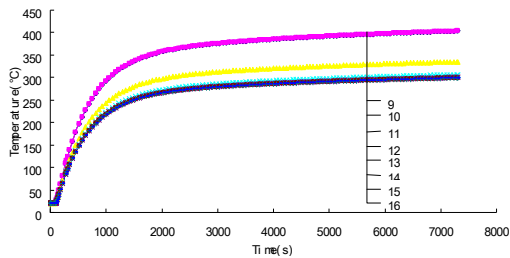
Based on the nonlinear finite element analysis, the distribution of the temperature field in Model 1 is shown in Figure 10. Considering the symmetry of the structure, the temperature curves of the 1/4 structure are given in Figure 10 (b) and (c). The eighth curve is in the center of the upper chord, and the ninth curve in the center of the lower chord. The others are chosen in turn along the symmetrical axis, and the distance is 3 m between every two curves. The temperature of the fire center is the highest in the upper chord, and it is 580 °C. The temperature decreases from the center to the edge of the structure, and the lowest temperature is 339 °C. The distribution of the temperature in the lower chord is similar, in which the highest and the lowest temperatures are 403 °C (the ninth curve) and 299 °C (the sixteenth curve), respectively. The results in the other Models are similar (not shown in this paper).



(a) Temperature map

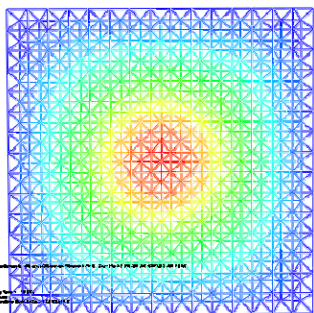


(b) The upper chord

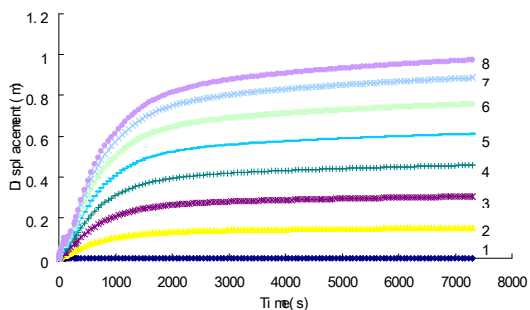


(c) The lowerer chord

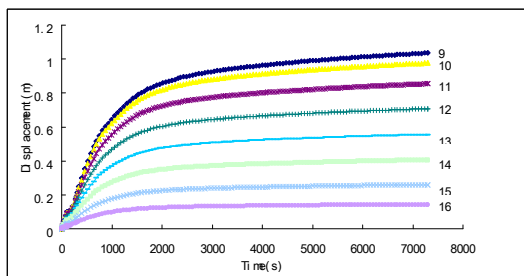
Figure 10: Temperature curves of the points on the space grid structure
 During the process of the numerical simulation, the fire sustained for about 2 hours. The displacement of the structure in Model 1 is shown in Figure 11, and the points are the same as Figure 10. Figure 11 shows that the displacements are the biggest in the structure center, and there are no sudden changes in all the displacements. The biggest displacement is 1.036 m, which is smaller than 1.575 m proposed by Jin [2]. Jin [2] suggested that the limit displacement of the structure is 3.5% of the calculation span when the whole structure collapses or can not bear any loads. Thus in the simulation, the structure does not collapse. The results are similar in the other Models (not shown in this paper).



(a) Displacement map



(b) The upper chord



(c) The lowerer chord

Figure 11: Displacements of the points on the space grid structure

However, the stresses of the members are changed suddenly within 2 hours in the simulations. The stresses of the members in the upper chord of Model 1 is shown in Figure 12. The sudden changes imply that the members failed. Four members of Model 1 failed in the fire center. Therefore, Figure 12 shows that the failure of the structure is partial, and the ultimate fire-resistant duration can be considered as 4414s. The other Models have the similar results (not shown in this paper). The ultimate fire-resistant durations of Model 2, 3, 4 and 5 are 2314s, 1102s, 3631s, and 3333s. All the failure modes are shown in Figure 13. Thus, at the same location of the fire, the bigger the area of the fire is, the more the failed members are, and the smaller the ultimate fire-resistant duration is correspondingly. As to the same area of the fire, the farther the distance from the fire center to the structure center is, the more the failed members are, and the smaller the ultimate fire-resistant duration is correspondingly too.

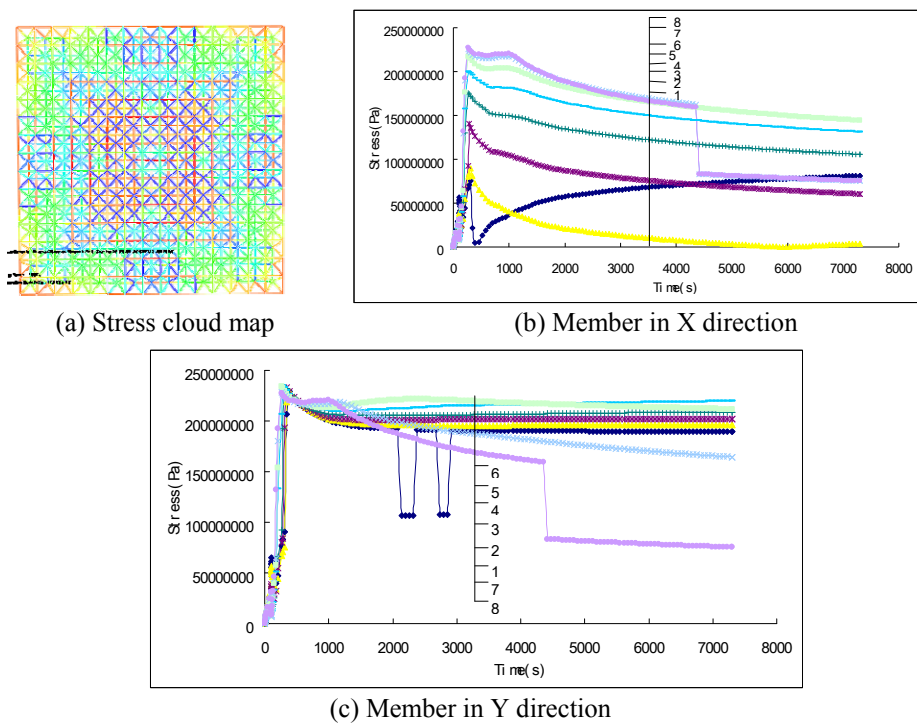
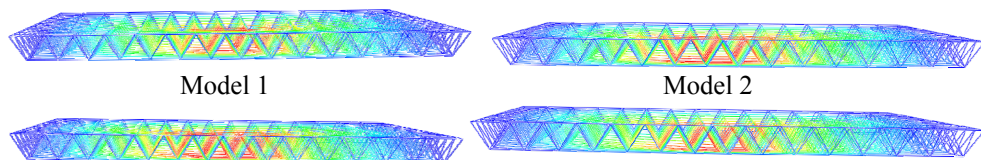


Figure 12: Stresses of members in the upper chord



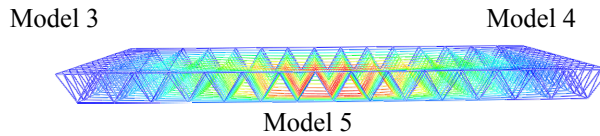


Figure 13: Failure modes of all Models

4. CONCLUSIONS

Based on the analyses, some conclusions can be drawn :

- (1) The temperature distributions of the welded hollow spherical joints under fire are uneven. The temperature of the equator is the highest, and that of the steel pipe root is the lowest. The ultimate fire-resistant durations of the joints under axial tension are longer than those under axial pressure. Decreasing the load ratio or increasing the thickness of the welded steel pipe can prolong the ultimate fire-resistant duration.
- (2) The root of the steel pipe failed prior to the welded hollow sphere, and it is the weakest part of the joint. In the failed specimen, there is no crack with the increase of the temperature, while the crack occurs when the temperature is decreasing because the stress of the joint is redistributed. This situation should be considered in design.
- (3) The failed members are located in the fire center. The larger the area of the fire is, the more the failed members are. The farther the distance from the fire center to the structure center is, the more the failed members are. And the ultimate fire-resistant duration decreases correspondingly. Therefore, the location of the fire has much greater effects on the space grid structure compared with the area of the fire, and the structure tends to collapse if the fire location is more unsymmetrical.
- (4) Part of the space grid structure failed under fire within 2 hours, which could result in the whole structure collapsing. Therefore, the conclusion in Jin [2] is not suitable for the space grid structures, and the structures must be retrofitted for reusing.

Acknowledgement

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