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Residual behavior of welded hollow spherical joints after exposure to elevated temperatures

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ABSTRACT

Welded hollow spherical joints are widely applied as main connection pattern in space lattice structures. During fire events, structures are inevitably exposed to elevated temperatures. Provided the general appearance of the structure remains satisfactory after a fire, the residual behavior of welded hollow spherical joints in these structures should be accurately estimated to ensure safety. However, the post-fire behavior of welded hollow spherical joints has not been explored in existing studies. Hence, experimental and numerical studies were conducted to reveal the post-fire residual mechanical behavior of welded hollow spherical joints. Seventeen specimens were initially heated to six various preselected temperatures up to 1000 °C and were subsequently cooled down to ambient temperature via two different methods: air cooling and water cooling. Axial compressive tests were then performed, and related mechanical properties, such as axial load–displacement curves, initial axial stiffness, yield loads, load-bearing capacities, ductility level, and strain distribution, were obtained and analyzed. The mechanical behavior of welded hollow spherical joints significantly changed after exposure to temperatures exceeding 600 °C, with phenomena of reductions in stiffness and strength but an increase in ductility level. Furthermore, the influences of different cooling methods were remarkable. A 3D finite element (FE) model was also developed using the ABAQUS software and validated against experimental results. Simplified design methods, based on parametric studies, were proposed to predict the post-fire residual load-bearing capacity and initial axial stiffness of welded hollow spherical joints.

1. Introduction

The joints used to connect tension and compression bars in space latticed structures mainly include MERO joints [1,2], Temcor joints [3,4], bolt-ball joints [5], socket joints [6], and welded hollow spherical joints. Welded hollow spherical joint, as a typical thin-walled connection member, possesses such advantages as light weight, high stiffness, simple in construction, easy to connect, and no node eccentricity. It was initially developed by X. L. Liu and first applied in Science & Technology Hall in Tianjin, China [7]. Since then, welded hollow spherical joints have been extensively used as a main connection pattern for space lattice structures particularly in China. Fire hazards are considered one of the main disasters that cause damage to building structures. Structures that involve the use of welded hollow spherical joints are inevitably exposed to elevated temperatures during a fire hazard. However, the entire structure may not collapse during a fire because of high design safety factor and proper fireproofing. Provided the general appearance of the structure with welded hollow spherical joints is satisfactory during and immediately following a fire event, its post-fire residual performance must be estimated correctly to determine whether the structure should be dismantled, repaired, or reused directly. Hence, the residual behavior of the welded hollow spherical joints after exposure to elevated temperatures must be investigated first to provide important basis for assessing the fire damage of the whole structure.

Existing literature include extensive studies on the mechanical behaviors of welded hollow spherical joints at ambient temperatures without fire exposure. Chen [8] and Zhou [9] conducted theoretical and experimental studies on the collapse mechanism and load-bearing capacity of welded hollow spherical joints with different diameters. Yao et al. [10] numerically investigated the load-bearing capacity of welded hollow spherical joints and proposed a practical calculation formula. Han et al. [11–13] developed formulas to calculate the load-bearing capacity and stiffness of welded hollow spherical joints subjected to compression, tension, and bending moment. Dong et al. [14] and Tang [15] studied the load-bearing capacity of welded hollow spherical joints

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under eccentric loads and developed design methods. Wan [16] and Wang et al. [17,18] numerically investigated the axial stiffness and rotational stiffness of welded hollow spherical joints and proposed calculation formulas. Liao and Zhang [19] studied the axial and rotational stiffness of welded hollow spherical joints and established a bilinear load-displacement model. Furthermore, design guides, such as JGJ 61-2003: Technical Specification for Latticed Shells [20] and JGJ 7-2010: Technical Specification for Frame Structures [21], also recommend design methods for welded hollow spherical joints.

Previous studies all focused on the performances of welded hollow spherical joints at ambient temperature; whereas no research has been reported on their mechanical behavior after exposure to elevated temperatures. Moreover, the available design standards did not provide applicable recommendations for the post-fire residual performances of welded hollow spherical joints.

In general, without comprehensive knowledge of the mechanical performances of welded hollow spherical joints after exposure to elevated temperatures, the post-fire evaluation of the residual behavior of structures with welded hollow spherical joints is not credible, which may induce uneconomical consequences or potential safety problems. In the current paper, experimental and numerical studies were performed to investigate the residual behavior of welded hollow spherical joints after exposure to elevated temperatures. The joint specimens were initially heated to six preselected elevated temperatures up to 1000 °C and subsequently cooled down to ambient temperatures through both air and water cooling methods. Axial compressive tests were then performed, and associated mechanical behaviors, such as failure modes, axial load–displacement curves, initial axial stiffness, yield loads, load-bearing capacities, ductility level, and strain distributions, were obtained and analyzed. Furthermore, a 3D finite element (FE) model was developed using the ABAQUS software and validated against the experimental results. Simplified design methods, based on parametric studies conducted using the validated FE model, were proposed to predict the residual load-bearing capacity and initial axial stiffness of welded hollow spherical joints after exposure to elevated temperatures.

2. Experimental investigation

2.1. Test specimens

Seventeen welded hollow spherical joint specimens were tested. The key parameters considered were exposure temperatures, cooling methods, and the steel grades of the specimens. Details of the specimens are shown in Table 1, where D and t refer to the external diameter and thickness of the hollow sphere, respectively; d, L, and t_s refer to the external diameter, length, and thickness of the steel tube, respectively; T refers to exposure temperature; and A and W refer to air and water cooling methods, respectively. An example of the naming method of the test specimen adopted in this study is J345-600-A, where J refers to the welded hollow spherical joint; the subsequent number refers to the steel grade of the specimen, i.e., Q345 steel or Q235 steel (with nominal yield strengths of 345 N/mm^2 and 235 N/mm^2, respectively); the following number refers to the elevated temperature the specimen had been exposed to, namely, 300 °C, 600 °C, 700 °C, 800 °C, 900 °C, or 1000 °C. The number 20, which was the ambient temperature in the laboratory, denotes specimens that were not exposed to fire. The external diameter of the hollow sphere, the thickness of the hollow sphere, and the external diameter of the steel tube are 200 mm, 8 mm, and 76 mm, respectively. The corresponding ratios of D/t and D/d are 25 and 2.63, respectively, which are consistent with the recommendations in JGJ 61-2003. In order to obtain the failure modes and load-bearing capacity of the hollow sphere, thickened steel tubes with a thickness of 10 mm were adopted for all specimens to ensure that the steel tubes do not fail before the hollow sphere does. Two enlarged end plates with thicknesses of 20 mm were welded to the top and bottom ends of the steel tubes. The quality of the butt weld that connects the steel tube and the hollow sphere meets the requirements of JGJ 61-2003. The test specimen details are shown in Fig. 1.

Table 1
Details of test specimens.

Joint number	$D \times t$ (mm)	$d \times L \times t_s$ (mm)	T (°C)	Cooling method	Steel grade
J345-20	200 × 8	76 × 50 × 10	–	–	Q345
J345-300-A	200 × 8	76 × 50 × 10	300	Air cooling	Q345
J345-300-W	200 × 8	76 × 50 × 10	300	Water cooling	Q345
J345-600-A	200 × 8	76 × 50 × 10	600	Air cooling	Q345
J345-600-W	200 × 8	76 × 50 × 10	600	Water cooling	Q345
J345-700-A	200 × 8	76 × 50 × 10	700	Air cooling	Q345
J345-700-W	200 × 8	76 × 50 × 10	700	Water cooling	Q345
J345-800-A	200 × 8	76 × 50 × 10	800	Air cooling	Q345
J345-800-W	200 × 8	76 × 50 × 10	800	Water cooling	Q345
J345-900-A	200 × 8	76 × 50 × 10	900	Air cooling	Q345
J345-900-W	200 × 8	76 × 50 × 10	900	Water cooling	Q345
J345-1000-A	200 × 8	76 × 50 × 10	1000	Air cooling	Q345
J345-1000-W	200 × 8	76 × 50 × 10	1000	Water cooling	Q345
J235-20	200 × 8	76 × 50 × 10	–	–	Q235
J235-600-A	200 × 8	76 × 50 × 10	600	Air cooling	Q235
J235-800-A	200 × 8	76 × 50 × 10	800	Air cooling	Q235
J235-1000-A	200 × 8	76 × 50 × 10	1000	Air cooling	Q235

2.2. Material properties

The structural steels used to manufacture the joint specimens are Q235 and Q345 hot-rolled steels, as suggested by JGJ61-2003. The qualities of the Q235 and Q345 steels used are in accordance with GB/T 700 [22] and GB/T 1591 [23], respectively. To determine the mechanical properties of the steels, tensile coupon tests were conducted on three Q345 and three Q235 standard coupons produced from the same batch of steels used to manufacture the joint specimens. The shapes and dimensions of the standard coupons are in accordance with GB/T 228.1-2010 [24], as shown in Fig. 2. The dimensions of each coupon were measured with a vernier caliper at three points within the gauge length. Average values were used to determine the mechanical properties of the steels. During the test process, the tensile load was applied at a tensile stress rate of 10 MPa/s during the elastic stage and at a constant strain rate of 0.001/s during yielding. Thereafter, loading was applied at a constant displacement rate of 10 mm/min until failure. The loading rates satisfied the requirements of GB/T 228-2010. The test results are listed in Table 2, where t_c is the thickness of the steel coupon, and E_s is the elastic modulus. f_y and f_u refer to the yield strength and ultimate strength, respectively; δ_u is strain at fracture, and ε_y denotes yield strain. Failure modes the obtained stress–strain relationships of the steel coupons are shown in Figs. 3 and 4, respectively. The Q345 and Q235 steels showed obvious ductile failure modes with necking, whereas higher-grade Q345 steel exhibited higher yield strength, ultimate strength, and yield ratio but lower ductility level than lower-grade Q235 steel.

2.3. Test conditions and procedure

The entire experimental process involved two steps. In the first step, the joint specimens were initially heated to the preselected elevated temperatures and subsequently cooled down to ambient temperature. In the second step, axial compressive tests were performed at ambient temperature. A temperature-controlled electric furnace was used to heat the specimens, as shown in Fig. 5. The thermocouple located inside the furnace measured the air temperature in the furnace and then relayed the measured temperature to the control system, which in turn