Journal of Constructional Steel Research 140 (2018) 108–124

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Behavior of welded hollow spherical joints after exposure to ISO-834 standard fire

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ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 6 October 2017
Accepted 21 October 2017
Available online xxxx

Keywords:
Welded hollow spherical joints
Post-fire
Residual behavior
Load-bearing capacity
Initial axial stiffness

ABSTRACT

Welded hollow spherical joints are extensively used as a connection pattern in space lattice structures. Provided that structural collapse does not occur after a fire, a reliable evaluation of the residual performances of the structures is necessary to decide whether the structures should be dismantled, repaired, or directly reused. Thus, understanding the post-fire residual behavior of welded hollow spherical joints, which act as key connection elements, is crucial for fire damage assessment of the space lattice structures. In this paper, experimental and numerical studies were conducted to reveal the residual structural behavior of welded hollow spherical joints after fire exposure. Axial compressive tests were performed on eight joint specimens after exposure to the ISO-834 standard fire (including both heating and cooling phases), and three highest fire temperatures, i.e., 600 °C, 800 °C, and 1000 °C, were considered. The temperature distributions in the specimens during the heating and cooling process and the related mechanical behavior of the specimens, such as axial load–displacement curves, initial axial stiffness, yield loads, load-bearing capacities, ductility level, and strain distributions, were obtained and analyzed. Finite element analysis (FEA), including both heat transfer and stress analysis, were also developed using the ABAQUS software. Having validated the FE models against the experimental results, a design method was proposed on the basis of parametric studies to predict both the residual load-bearing capacity and initial axial stiffness of welded hollow spherical joints after fire exposure.

1. Introduction

As a typical large-span structural form, space lattice structures are formed by a large number of tension and compression bars connected with joints. The joints widely used in space lattice structures mainly include MERO joints [1,2], Temcor joints [3], bolt–ball joints [4], socket joints [5], and welded hollow spherical joints etc. The welded hollow spherical joints were initially developed by X. L. Liu and first applied in the Science and Technology Hall in Tianjin, China [6]. This joint pattern possesses such advantages as light weight, high stiffness, simple in construction, easy to connect, and absence of node eccentricity. Thus, this joint pattern has been extensively used in space lattice structures, particularly in China. Structures involving the use of welded hollow spherical joints may be exposed to elevated temperatures in the event of a severe fire hazard, which is typically considered as one of the main disasters causing damages to building structures. Nevertheless, provided that a sufficiently high design safety factor and proper fire insulation are provided, structural collapse of the entire space lattice structure is unlikely to occur in a real fire. If the response of the structure is satisfactory during and immediately following a fire event, then its post-fire residual performance must be evaluated accurately to determine whether the structure should be dismantled, repaired, or reused directly. Therefore, as an important basis of assessing the fire damage of the entire structure, the post-fire residual behavior of the welded hollow spherical joints, which act as key connection members, must be investigated first.

Extensive studies have been conducted to investigate the mechanical behavior of welded hollow spherical joints at ambient temperature without fire exposure. Chen [7] and Zhou [8] conducted both theoretical and experimental studies on the collapse mechanism and load-bearing capacity of welded hollow spherical joints with different diameters. Han et al. [9–11] proposed formulas to calculate the load-bearing capacity and stiffness of welded hollow spherical joints subjected to compression, tension, and bending moment via theoretical and numerical analysis. Dong [12] and Tang [13] investigated the load-bearing capacity of welded hollow spherical joints under eccentric loads and developed a practical calculation method. Wan [14] and Wang et al. [15,16] conducted finite element analysis (FEA) to investigate the axial and rotational stiffness of welded hollow spherical joints and proposed the calculation formulas. Zhang et al. [17] investigated the axial and rotational stiffness

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https://doi.org/10.1016/j.jcsr.2017.10.026
0143-974X/

Table 1
Details of the test specimens.

Specimen no.	T_h (°C)	t_h (min)	Steel grade
J345-20	–	–	Q345
J345-600	600	5.9	Q345
J345-800	800	22.7	Q345
J345-1000	1000	86.4	Q345
J235-20	–	–	Q235
J235-600	600	5.9	Q235
J235-800	800	22.7	Q235
J235-1000	1000	86.4	Q235

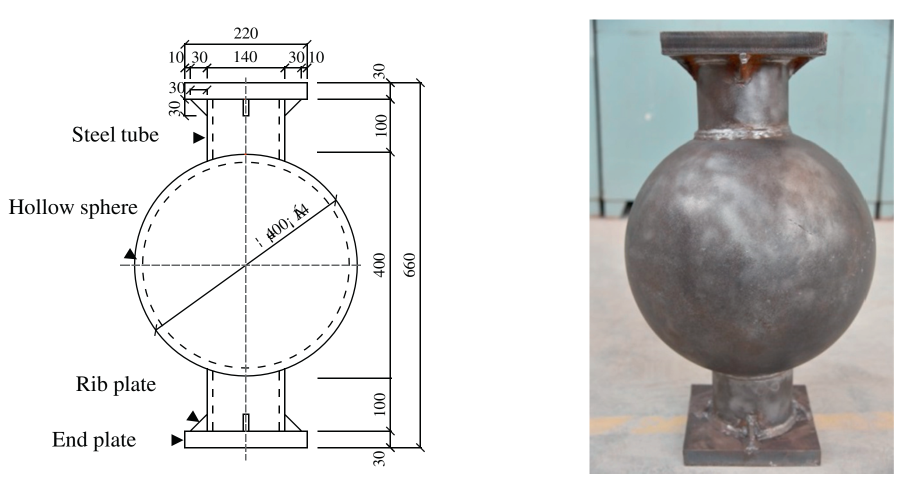
of welded hollow spherical joints and established a bilinear load–displacement model. Furthermore, design guides, such as JGJ 61-2003: Technical Specification for Latticed Shells [18] and JGJ 7-2010: Technical Specification for Frame Structures [19], also provide the design methods for welded hollow spherical joints. According to the brief literature review, previous studies have all focused on the mechanical behavior of welded hollow spherical joints at ambient temperature. However, it is known that the mechanical properties of structural steels will significantly change after exposure to elevated temperatures, which will lead to obvious changes in the behavior of welded hollow spherical joints further. What's more, some geometric imperfections induced by heating-cooling process might also be introduced in the welded hollow spherical joints, which will also influence the post-fire behavior of the joints. Hence, it is not appropriate to directly apply the research results obtained from ambient temperature to the assessment of the performance of welded hollow spherical joints after fire exposure. Nevertheless, no reported research on their mechanical performance after fire exposure has been found. Furthermore, no current design guide has provided applicable recommendations for the post-fire residual performance of the welded hollow spherical joints.

Generally, without comprehensive knowledge of the mechanical performances of welded hollow spherical joints after fire exposure, the post-fire assessment on the behavior of the structures involving the use of these joints is unconvincing. Such results will lead to an uneconomical consequence or potential safety problem. This paper presents the details of the experimental and numerical studies on the post-fire behavior of the welded hollow spherical joints. Eight joint specimens were initially exposed to the ISO-834 standard fire [20] (including both heating and cooling phases) with three different highest fire temperatures of up to 1000 °C. The temperature distributions in the specimens were measured during the heating and cooling process. Axial compressive tests were subsequently performed on the specimens at ambient temperature to investigate their post-fire fundamental behavior. Related mechanical properties, such as axial load–displacement curves, initial axial stiffness, yield loads, load-bearing capacities, ductility level, and strain distributions, were obtained. Furthermore, finite element analysis, including both the heat transfer and stress analysis, were developed using ABAQUS software. On the basis of parametric studies, a design method was proposed to predict the residual load-bearing capacity and initial axial stiffness of welded hollow spherical joints after fire exposure.

2. Experimental investigation

2.1. Test specimens

A total of eight welded hollow spherical joint specimens were tested. The key parameters considered were the highest exposure fire temperatures (corresponding to the heating time based on the ISO-834 standard temperature–time curves) and the steel grades of the specimens. Details of the specimens are shown in Table 1, where T_h and t_h refer to the highest exposure fire temperatures and corresponding heating time, respectively. An example of the naming method of the test specimen is as follows: J345-20, where J refers to the welded hollow spherical joint; the next three digits refer to the steel grade of the specimen, i.e., Q345 or Q235 steel (with nominal yield strengths of 345 and 235 N/mm^2, respectively); and the following number refers to the highest exposure fire temperature experienced, i.e., 600 °C, 800 °C, or 1000 °C; whereas number 20, which was the ambient temperature of the laboratory, denotes the specimens without fire exposure. For all test specimens, the external diameter (D) and thickness of the hollow sphere (t) and the external diameter of the steel tube (d) maintained 400 mm, 14 mm, and 140 mm, respectively, which are the commonly used dimensions in practical projects. The corresponding ratios of D/t and D/d are 28.57 and 2.86, respectively, which are in accordance with the recommendations in JGJ 61-2003. Relatively thick steel tubes with a thickness of 10 mm were used for all specimens to obtain the failure modes and load-bearing capacity of the hollow sphere. Two enlarged end plates with a thickness of 30 mm were welded to the top and bottom ends of the steel tubes. The quality of the butt weld connecting the steel tube and the hollow sphere meets the requirements of JGJ 61-2003. The test specimen details are shown in Fig. 1.



(a) Details of the specimen (mm)

(b) Specimen photograph

Fig. 1. Test specimen.