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Mechanical behavior of Ring-sleeve joints of single-layer reticulated shells

Ruo-qiang Feng [a,*], Feng-cheng Liu [b], Guirong Yan [c], Xiao-liang Chang [d]

[a] School of Civil Engineering, Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing 210096, China
[b] School of Civil Engineering, Southeast University, Nanjing 210096, China
[c] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, 1401 N. Pine St., Rolla, MO, United States
[d] School of Civil Engineering, Southeast University, Nanjing 210096, China

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ABSTRACT

The type of joint used is important in the stability of single-layer reticulated shells. In this paper, a new type of bolted joint called the Ring-sleeve joint, which is suitable for single-layer reticulated shells, is proposed. Prototype static experiments and numerical analyses were conducted to study the mechanical behaviors of this joint. The bending moment, the shear force, and the axial force were all considered. The main conclusions are as follows. First, there are three failure modes of these joints, depending on the ratio of the bearing capacity of the bolts to the bearing capacity of the tube. The first failure mode observed was that the full sections of all bolts yielded first, and then the tube buckled. The second failure mode was that tube buckled with part of the bolt section in a plastic state. The third failure mode was that the full sections of all bolts yielded, but the tube did not buckle. The Ring-sleeve joints in the former two failure modes have good bearing capacity and ductility, according to the experimental and numerical results.

1. Introduction

The tube and joint are two important components of single-layer spatial reticulated shells. The mechanical behaviors of the joint, such as strength and bending stiffness, have a great influence on the mechanical behavior of the structure. Observations from earlier studies by See [1] and Fathelbab [2] confirmed that joint stiffness has a considerable effect on the load-displacement behavior of a structure. In addition, substantial savings in materials and cost can be achieved if the effects of the actual joint properties are considered in the design. EI-Sheikh [3] and Shibata [4] found that the behavior of a structure with hinged joints is different from the behavior of a structure with rigid joints. Atiziber Lopez [5–6], in Spain, found by numerical analysis that the ultimate load capacity of a structure with hinged joints is likewise different from that with rigid joints. Kato S [7] also verified that the rigidity of the joint is an important factor that influences the behavior of a single-layer latticed dome. Fan Feng and Ma Quichuan [8] investigated the moment-rotation characteristics of bolt-ball joints experimentally and numerically. For a Kewitte dome with a span of 30 m and a rise-span ratio of 1/8, when the joint stiffness is five times the stiffness of the bolted-ball joint, the structure acts as a rigid dome; when the joint stiffness is 3% of the stiffness of the bolted-ball joint, the structure is unstable subject to loads. Chenaghlou [9–10] investigated the mechanic behavior of MERO ball joint with different combinations of axial forces and bending moments by experiments and numerical simulation, and he concluded that axial forces decreases the ultimate moment capacity of the connection.

Currently, the Mero joint system is widely used in spatial structures. The Mero-1 joint system invented by Max Mengeringhausen in 1943 is well-known as a bolted-ball joint. Mero-2, Mero-3, and Mero-4 joint system can be used in different types of single-layer spatial reticulated shells. The Mero-4 joint system is used in the New Milan Trade Fair by Stephan [11]. The Triodetic joint system from Canada is mainly used in double-layer structures. The SBP (Schlaich bergermann partner) joint system, including SBP-1, SBP-2, and SBP-3 joints, can be used in different types of structures, including the cable-braced grid shells described by Stephan [11]. Feng [12] improved the SBP-1 joint by adding a steel shim so that the new joint achieved better mechanical behavior. The FF joint system from Germany, developed by Novum Company, is also widely used, and the Temcor joint system from America is used in many aluminum alloy structures.

This paper proposes a new type of bolted joint called the Ring-sleeve joint, which is suitable for single-layer spatial reticulated structures. This joint is simple to produce and convenient to install, which has easily understood mechanical behavior. It offers good performance in redundancy and security. Prototype static

* Corresponding author.
E-mail addresses: hitfeng@163.com (R. Feng), lfc110@163.com (F. Liu), yang@mst.edu (G. Yan), 54442965@qq.com (X. Chang).

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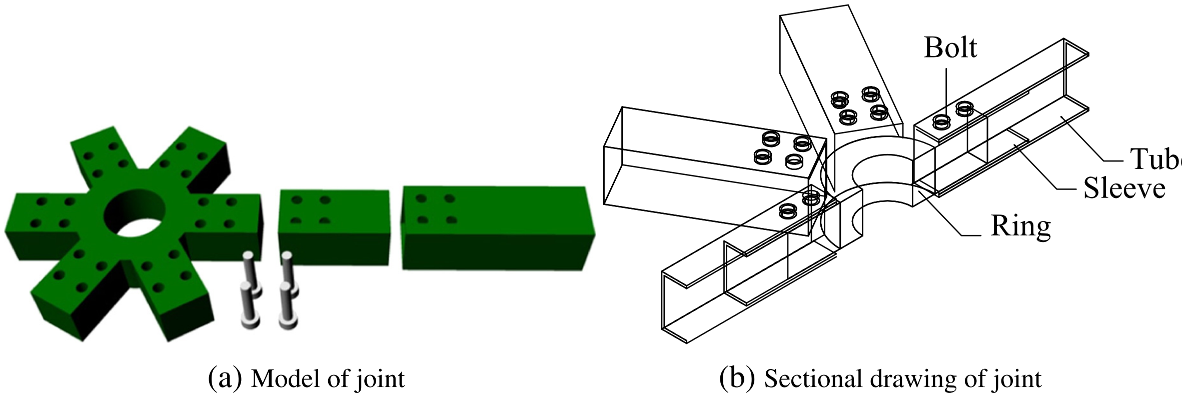

Fig. 1. Schematic diagram of joint.

experiments and numerical analyses were performed to study the mechanical behaviors of the joint.

2. Test program

2.1. Construction details of Ring-sleeve joint

The details of the construction of the Ring-sleeve joint are shown as a sectional drawing in Fig. 1. The joint consists of a central ring, sleeves, tubes and high-strength bolts. There are identical bolt holes in the central ring, sleeve and tube. The bolt holes of the central ring, sleeves and tubes are aligned to assemble the joint using the high-strength bolts. The construction details of Ring-sleeve joint help to offers good performance in redundancy and security (Even when the bolts bend or the pipe buckled, the joint still has some bearing capacity).

2.2. Force conditions of tubes

The joint studied came from a geodesic single-layer spherical reticulated shell with a span of 53 m, a rise-span ratio of 0.3 and a radius of 30 m, as shown in Fig. 2. A square steel tube with dimensions 100 mm × 100 mm × 4 mm made of Q390 steel was used. The structural boundary conditions were hinged.

The dead load of the shell was as follows: the building envelope of the roof was toughened glass, the thickness was 20 mm, and the density was 25.6 kN/m^3, in addition to the self-weight of the steel tubes. The live load was 0.5 kN/m^2, according to “Load code for the design of building structures” by the Ministry of Construction [13]. The design load of the structure was 1.35 × dead load + 1.4 × live load.

The finite-element software called ANSYS by ANSYS Inc., Canonsburg PA [14] was used for the FEA (Finite Element Analysis). The beam element Beam188 was used to simulate the tube. The stress level of the tubes is shown in Fig. 3. The horizontal axis is the maximum stress of the tube, and the ordinate axis is the ratio of the bending stress to the axial stress.

In Fig. 3, each spot represents one tube. Considering the adverse stress condition of the tube, 0.46 is chosen as the ratio of bending stress to axial stress of the tube for the joint experiment.

2.3. Joint design for experiment

As the joint is symmetric, to investigate the connection between the central ring and tube, the joint in the experiment can be simplified as shown in Fig. 4(a). The central ring was cut into two parts. The cutting surface and a slab were welded together for convenient installation and support of the whole experimental joint. The shear force and moment of the tube were applied through the lateral force acting on two ear-plates welded at the end of the tube. The details of the experimental joint are shown in Fig. 4(b), and the details of the sleeve are shown in Fig. 4(c).

2.3.1. Radius of ring R1, R2

First, the outside diameter R2 was confirmed according to the geometric construction of the joint. In the single-layer spherical reticulated shell, one joint was connected to 6 tubes, and there should

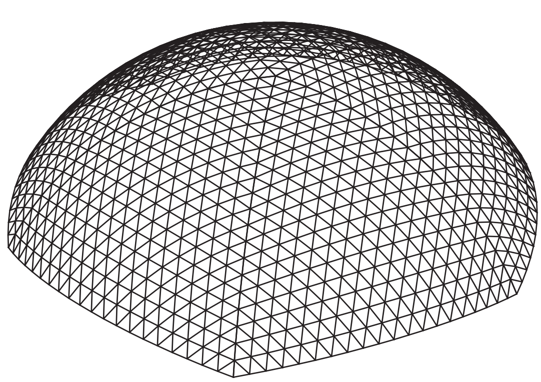

Fig. 2. Diagram of spherical shell.

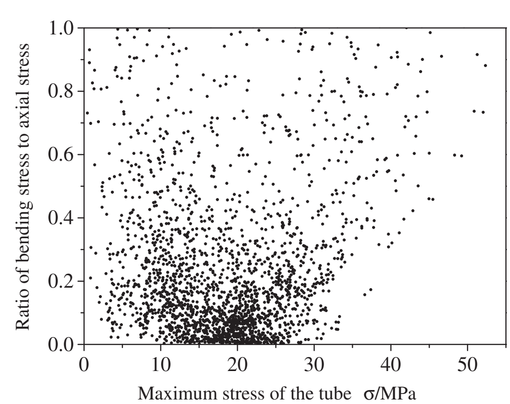

Fig. 3. Stress level of tubes in spherical shell.