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Static performance of double-ring joints for freeform single-layer grid shells subjected to a bending moment and shear force

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ABSTRACT

This paper discussed a new type of bolted joint named a double-ring joint used in freeform single-layer grid shells. Prototype static tests and numerical simulations were undertaken to investigate the mechanical behavior of the bolted joint subjected to the bending moment and shear force. The main conclusions of this study are as follows. There are two primary failure modes of double-ring joints. One is the fracture of the bolt, and the other is the instability of the central ring. The failure mode depends only on the ratio of the ring thickness to the ring diameter when the height of the ring and the diameter of the bolt match. Ultimately, the simplified formulae for the load-bearing capacity of a double-ring joint in different failure modes were proposed as a reference for joint design.

1. Introduction

In the last two decades, single-layer grid shells with complex curved surfaces have been envisaged to cover new leisure and transportation spaces. Currently, welded and bolted connections are the main connections in single-layer grid shells. Welding connections on site requires a substantial amount of time and manpower, and high quality is not easily guaranteed. In contrast, bolted connections can reduce construction time and ensure construction quality.

Various types of bolted joints have been proposed, such as the Mero joint by Max Mengeringhausen [1], the Triodetic joint by Fentimen Company [2], the SBP joint system by Schlaich Bergermann Partner [3], and the Temcor joint by Temcor Company. Both experimental and numerical studies have been conducted on the mechanical behavior of bolted joints, indicating that this behavior is different from that of rigid joints or pinned joints. Feng [4,5] investigated the failure mode and mechanism of ring-sleeve joints in triangular mesh and bolted joints in quadrangular mesh subjected to an axial force, bending moment, and shear force. This study confirmed that bolted joints are semi-rigid joints. Fan and Ma [6] discussed the moment-rotation characteristics for two typical bolted joints subjected to bending with and without axial force and indicated that axial compressive force could increase the initial bending stiffness of the joint. In addition, Chenaghlou [7,8] found that the axial force influenced the bearing capacity of the MERO ball joint experimentally and numerically, concluding that the axial force reduced the bearing capacity of the joint.

The effect of the stiffness of connections on the behavior of grid shells was found to be significant by Feng [9,10]. Earlier work carried out by See [11], Fathelbab [12,13] and EI-Sheikh [14] confirmed that joint rigidity had a significant influence on the mechanical behavior of shells. López A. [15,16], Kato [17] and Wang [18] used numerical analyses to determine that joint stiffness greatly impacted the behavior of a single-layer grid shell, and the bearing capacities of a grid shell with hinged joints and a grid shell with rigid joints were different. Ma [19,20] conducted an experiment and confirmed the effect of the bolted stiffness on the stability of cylindrical and elliptical paraboloid grid shells. Liu [21,22] also investigated that the semi-rigidity of the Temcor joint could noticeably reduce the global rigidity and stability bearing capacity of the latticed shell.

There are some practical applications of the similar connection, such as the freeform lighting roof of Yueda Square in Shanghai, as shown in Fig. 1. The bolted joint, as shown in Fig. 2, is used in the freeform lighting roof of Yueda Square in Shanghai.

This paper studied the static performance of a double-ring joint subjected to the bending moment and shear force, including the load-bearing capacity, the failure modes and practical design method. This joint is easy to prefabricate and has adequate security and applicability. Prototype static experiments, numerical simulations and theoretical

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Fig. 1. The freeform lighting roof of Yueda Square in Shanghai.

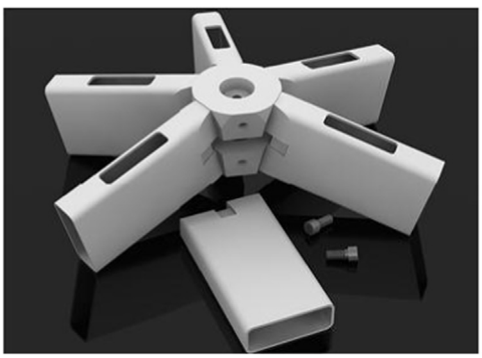

Fig. 2. Bolted joint.

analysis were conducted to discuss the static performance of double-ring joints subjected to the bending moment and shear force in this paper.

2. Test program

2.1. Details of double-ring joints

The double-ring joint consists of two central rings, sealing plates, tubes and high-strength bolts, as shown in Fig. 3. The high-strength bolts were fixed on the sealing plate by spot welding, and the sealing plate was connected with the tube by butt welding, as shown in Fig. 3(c). The central ring and tubes were connected by tightening the high-strength bolts. This joint can be easily installed by using bolts onsite, in contrast to the constructive difficulties of a welded connection.

Besides the rectangular hollow section, the I-shaped section can also be used in the double-ring joint, as show in Fig. 4. First, set two threaded holes in the sealing plate. Second, connect the end of the I-shaped member with the sealing plate by butt welding. At last, connect the central ring with the member by tightening the high-strength bolts. This paper only discussed the double-ring joint with rectangular hollow sections.

2.2. Parameter design for the experiment

Due to the symmetry of the joint, the joint in the test can be simplified into two tubes, as shown in Fig. 5(a). The basic parameters of the double-ring joint for the experiment shown in Fig. 5 are designed as follows.

2.2.1. Tube section

According to the "Technical specification for space frame structures" by the Ministry of Construction [23], the slenderness ratio of the pressure-bending member in a single-layer grid shell is defined as

$$\lambda_x = \frac{l_{0x}}{i_x} \tag{1}$$

$$\lambda_y = \frac{l_{0y}}{i_y} \tag{2}$$

where λ_x and λ_y are the out-of-plane and in-plane slenderness ratios of the member in a single-layer grid shell, respectively; l_{0x} is the out-of-plane effective length of the member, $l_{0x} = 1.6l$; l_{0y} is the in-plane effective length of the member, $l_{0y} = 1.0l$; l is the geometric length of the member; and i_x and i_y are the out-of-plane and in-plane radii of gyration

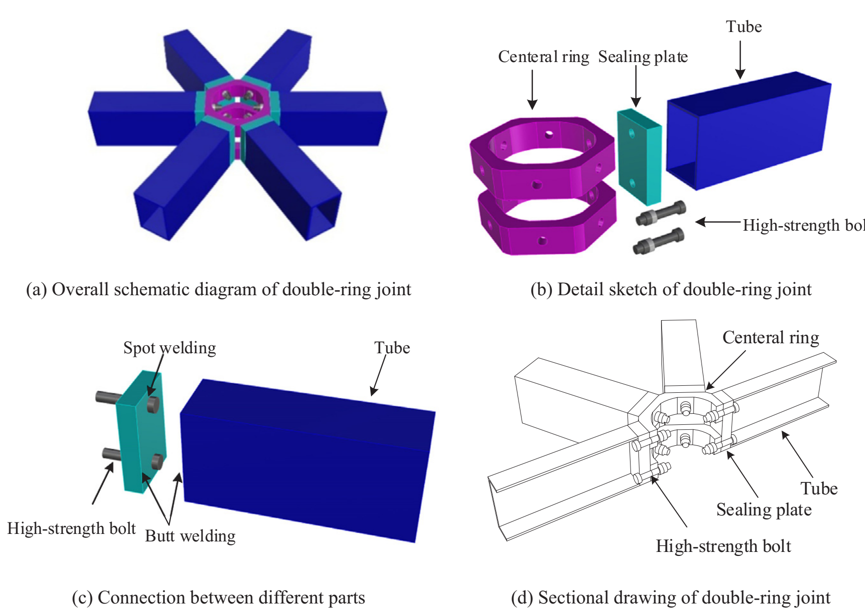

Fig. 3. Schematic diagram of double-ring joint.