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In-plane bending hysteretic behavior of cruciform diaphragm welded joints with axial force

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A R T I C L E I N F O

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A B S T R A C T

Cruciform diaphragm welded joints (CDWJ) has been adopted in large-span single-layer latticed shell as a new type of joint. The behavior of such kind of joint has not been well studied and understood. In this paper, the in-plane bending hysteretic behavior with axial force of CDWJ was investigated by performing both experimental tests in full scale prototypes and nonlinear numerical analyses. The results in terms of behavior, ultimate load and collapse mode were analyzed and compared. Experimental and numerical analysis results had good agreement for the CDWJ. Parametric analysis was performed on 14 CDWJ considering the influence of geometric size of components, angle between tubes and the axial compressive ratio. Moreover, Menegotto-Pinto mathematical model was established to describe the nonlinear rotation stiffness of CDWJ.

The tubular steel members used in space truss can be RHS (rectangular hollow sections), CHS (circular hollow section), or a combination of CHS and RHS. Different types of connections can be used in tubular structural systems, such as: welded hollow spherical joints, socket joints, plate joints, hollow section joints and other joint systems. For the cases of welded trusses, one of the most popular joints is the hollow section joint. Recently, based on the hollow section joint, a new type of tube-plate joint, named as the cruciform diaphragm welded joint (CDWJ), was developed and adopted in the roof of Yujiapu railway station, the largest single-layer latticed shell in China now.

Yujiapu railway station is located in Tianjin, China. The station has a conch-shaped single-layer latticed shell roof, which is 142 m long, 80 m wide and 24 m high. The main members of the shell are 72 curved steel box girders that intersect one another, as shown in Fig. 1 [1]. Two ring beams were set on the top and the bottom of the shell respectively to connect and constrain the steel box girders. The region in the middle of the structure, supported by 42 short columns fixed on the top ring beam, was constructed with CHS members as the skylight.

Details and basic forms of the new cruciform diaphragm welded joints adopted in the roof are shown in Fig. 2. Both RHS and CHS members could be connected with this type of tube plate joint. Because of its simple form and excellent stiffness properties, the cruciform diaphragm welded joint has a potentially application prospect in large span steel structures. However, as the most important component in the space structure with the action of connecting members and transferring loadings, the design of joint is really a significant and difficult problem. Therefore, the behavior of cruciform diaphragm welded joint has to be studied carefully to obtain its failure mechanism and design basis. Moreover, in the design of reticulated space structures, the common practice over the years has been to consider the joints as being pinned. However, when moving onto single-layer latticed structures, pinned joints are of no help in achieving the required stability and resistance [2]. Obviously, they cannot be regarded as rigid joints either [3]. Therefore, researchers pay more attention to the actual nonlinear stiffness of joints in single-layer spatial structures to find an appropriate joint design which can provide the structure with enough stiffness to satisfy various design rules.

Lopez et al. [3] calibrated the initial rotational stiffness of a semi-rigid joint that may be used in single-layer structures based on a series experimental results and then proposed an analytical method for the determination of initial rotational stiffness of that joint. Ma et al. [4] analyzed several finite element models to obtain moment-rotation relationships for socket joints subjected to uniaxial compression. Chenaghlou [5] established an exponential mathematical model for prediction of moment-rotation behavior of semi-rigid MERO bolted ball joints in space structures. Ahmadizadeh and Maalek [6] also investigated the effects of socket joint deformability on the behavior of space grid structures. The load-deformation relationships obtained from a series of biaxial loading tests on actual socket joints have been used to represent their behavior in several finite-element analysis structure models.

Although most of these existing researches are focus on the static behavior of the joints, whereas many of the large-span steel structures are servicing in the regions of high seismic risk, leading to the great

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Fig. 1. Yujiapu railway station in Tianjin, China.

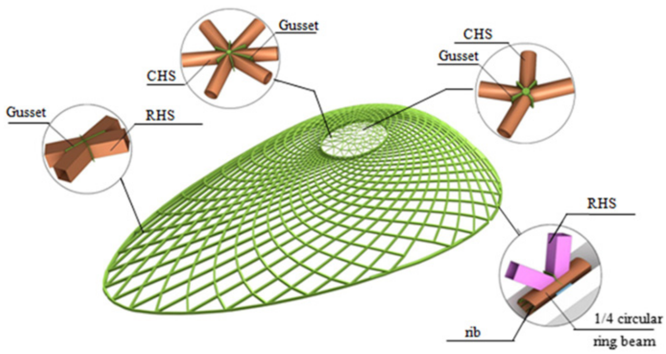

Fig. 2. Joints in the roof of Yujiapu railway station.

concerns from the engineering community about the behavior of joints under seismic loading.

During a strong earthquake event in practice, members of reticulated shells are subjected to load in three directions with a complicated stress state. Although membrane actions are dominant in shell-shaped structures, both the dynamic and static characteristics of single-layer latticed shells significantly depend on their configurations [7]. Therefore, it is necessary to investigate the spatial hysteretic behavior of members and joints under the interaction between the compression and biaxial bending [8]. In fact, the out-of-plane bending moments in components of single-layer latticed shells are predominant in most cases. However, in most literatures, the combined axial force and in-plane bending tests were always performed on joints for its easier availability [9]. This paper also starts research job on CDWJ considering only the effect of the combined actions of axial force and the in-plane bending.

The paper aims to establish the moment-rotation relationship for cruciform diaphragm welded joints subjected to cyclic in-plane bending load. The experiments of three full-scale cruciform diaphragm welded joints under low cycle cyclic loading are reported. After the numerical simulation method is verified using two experimental results, parametric analysis is performed to know how the combination of different parameters can influence the stiffness of the joint and its rotational capacity. Moreover, Menegotto-Pinto mathematical model is established to describe the nonlinear rotation stiffness of joints. Research results of this paper will apply scientific proof and technical support to the development of cruciform diaphragm welded joints. Considering CHS is the most common selection for primary load-carrying members of large-span steel structures, CHS cruciform diaphragm welded joints are studied in this paper.

1. Experimental procedure and results

As shown in the roof of Yujiapu railway station in Fig. 2, CDWJ could be used to connect 4 to 6 rectangle or circular tubes at the same time. Simple CDWJ composes of the main tubes, branch tubes and intersecting cruciform diaphragms. Considering CHS members are more popular than RHS members in many applications and the out-of-plane intersection angles of tubes are small in practical shallow roof structures, the CDWJ studied in the paper are in-plane simple CHS joints ignoring the influence of out-of-plane forces, as shown in Fig. 3.

1.1. Test specimens

Tests have been conducted on several full-scale CDWJ specimens which have been carefully designed to represent the geometry of joints generally used in single-layer latticed roofs in practice. The test specimens were fabricated with the main tubes and branch tubes perpendicular to each other. Three specimens were fabricated from Q235B hot-rolled CHS tubular sections and plates with different sizes of the branch tubes. Experiments on the CDWJ were performed with axial compression force applied on the tubes. Fig. 4 shows the general layout and the main dimensions of the joints.

1.2. Test setup

Fig. 5 shows the general test arrangement of the joint. The ends of the two short CHS members were bolted to a reaction frame and to the strong floor of the laboratory. The horizontal and vertical jacks applied compressive loads on the joint. In-plane bending moment was produced by a second horizontal jack at the top of the joint with cyclic lateral displacements.

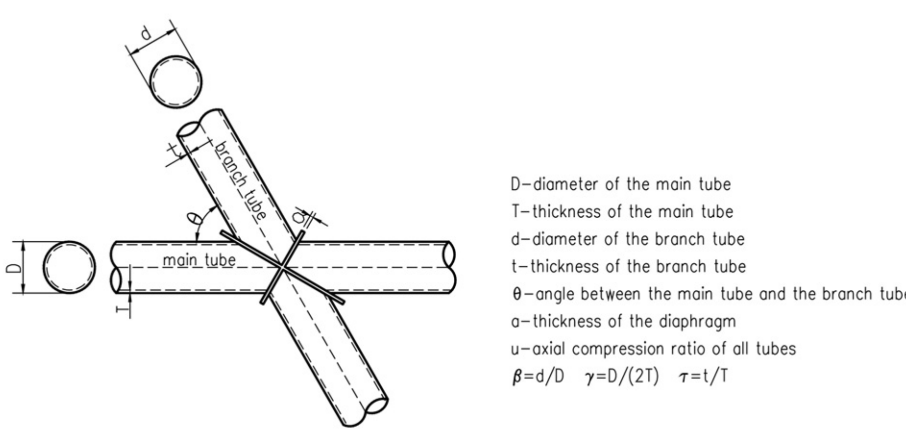

Fig. 3. The layout of CDWJ and the geometric parameters.