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An automatic three-dimensional loading apparatus for static tests of truss joints

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ABSTRACT

Static tests of truss joints are extremely important in investigating their mechanical behavior and collapse mechanisms. Traditional test apparatuses are especially designed to provide desired constraints and loading forces to specific joints, which leads to low testing efficiency and subsequently to high costs if tests of different joints are needed. This paper proposes a spherical three-dimensional loading apparatus which has wider universality and higher automaticity compared to the traditional ones. The apparatus consists of a hollow spherical frame, a spatial positioning mechanism, a hydraulic loading system and a control system. The loading actuators can be automatically positioned at the desired three-dimensional locations for different joints. This apparatus has been applied to test newly designed joints of the Shanghai World Expo and the Hangzhou East railway station in China successfully, and the only changes that required different tests are the repositioning of the loading actuators and applying of different forces to the joints automatically. Therefore, the proposed apparatus provides a large increase in universality over previous designs.

1. Introduction

Truss structures are widely used as an excellent structural form in many applications, such as buildings and bridges [1–3]. Their advantages include mass production, easy transportation, fast assembly, light weight and aesthetic qualities [4]. The mechanical properties of truss joints are difficult to theoretically predict due to imperfections in materials and connections, imprecision of shapes and dimensions, and uneven forces in bolt connections [5]. Therefore, experimental tests of truss joints are extremely important and indispensable especially for newly designed joints.

Hydraulic loading apparatuses are widely used to apply loading forces to truss joints in laboratories owing to their advantages of high power density ratio and good control performance. A hydraulic loading apparatus generally consists of a support frame, a hydraulic circuit, and a control system [6–8]. Fig. 1(a) illustrates a typical loading apparatus for static tests of tubular K-joints [9]. The support frame and the installation method of hydraulic cylinders should be designed particularly to provide desired constraints and loading forces to the tested joint, and the stiffness and strength of the frame should be sufficiently large to avoid structural damage and unpredictable influences. Accordingly, this loading apparatus cannot be directly used to test other kinds of truss joints (e.g., X-joints and KK-joints) unless it is reassembled by the following procedures, as illustrated in Fig. 1(b) for KK-joints. Firstly, the original frame should be repositioned and refixed. Then other hydraulic cylinders and reaction frames should be fabricated, positioned and fixed. Considering that all the steps are carried out artificially, it is time-consuming and expensive to adopt traditional apparatuses if static tests of different truss joints are required.

As shown in Fig. 2(a) [10], an alternative method by introducing a self-balanced frame can be used to improve the universality of loading apparatuses, as different joints can be fixed or restrained in the identical frame. A toroidal loading apparatus shown in Fig. 2(b) was utilized by Guo et al. [11], which reveals that the loading actuators and the restraints can be installed at any place on the circular frame. Chen et al. [12] presented a planar self-balanced reaction frame depicted in Fig. 2(c), in which the tensile forces in varying directions can be applied by using different ear plates welded in the frame beam. However, the loading direction cannot be continuously adjusted, so the flexibility of the loading apparatus is limited.

Static tests of three-dimensional joints are more complicated than those of two-dimensional joints mentioned above because of more diverse restraints and force conditions. Fig. 2(d) shows a typical loading apparatus for three-dimensional joints [13]. Several frames (the vertical frame, the inclined frame and the end support) should be appropriately positioned and bolted down to the strong floor. Also, the truss joints can be positioned and fixed in a self-balanced frame [14] so that the identical frame can be applied to test different truss joints. Different frames

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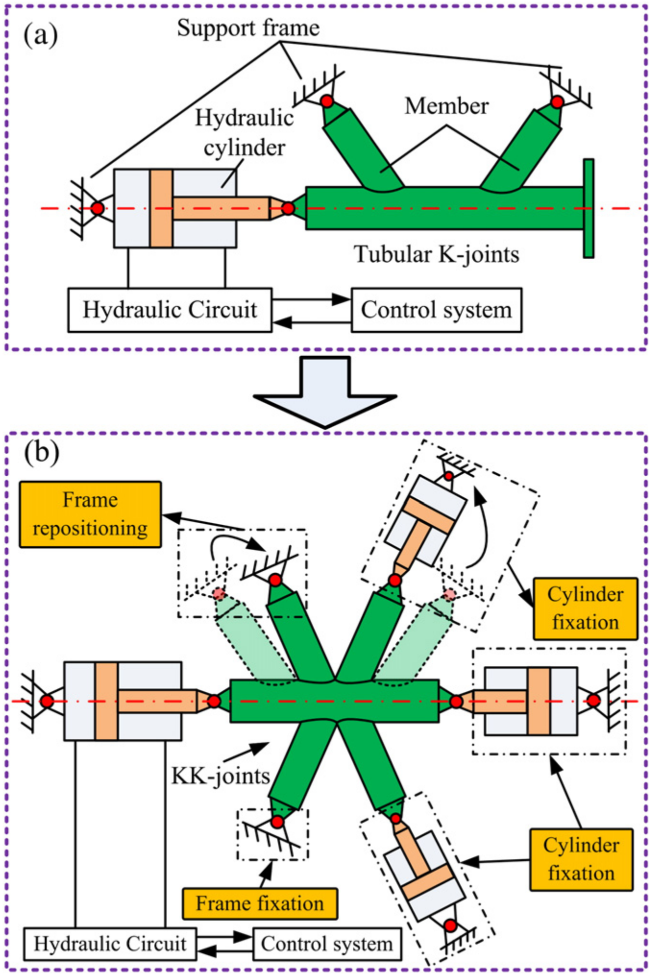

Fig. 1. Schematic diagram of a typical loading apparatus for different truss joints.

shown in Fig. 2(f)–(h) [15–17] are proposed to enable them to test more types of truss joints. Although the universality of the loading apparatuses is improved, the positioning and fixing assignments are still carried out artificially with low testing efficiency.

In recent years, a large number of three-dimensional truss joints have been developed rapidly and applied increasingly to new bridges and buildings to cover larger span areas with few materials and sufficient strength or to achieve more attractive architectural appearance [18]. However, the test requirement cannot be satisfied by adopting traditional experimental apparatuses featured with low universality, low efficiency and high costs. To overcome this difficulty, a universal three-dimensional loading apparatus is proposed in this paper. Different truss joints can be tested more efficiently without redesigning the support frame and the fixation of loading actuators. The rest of this paper is structured as follows: The design of both the mechanical system and the control system is introduced in Section 2. Section 3 describes the experimental method and the applications. Finally, the conclusions are drawn in Section 4.

2. System design

2.1. Basic principle

The schematic of the proposed loading apparatus is shown in Fig. 3. The proposed apparatus is composed of four main parts: a spherical support frame, a spatial positioning mechanism, a hydraulic loading system, and a control system. The frame of the loading system is a self-balanced hollow spherical steel structure, in which the mechanical components, the hydraulic actuators and the tested joint are placed. The joint is attached to the foundation; specific loading forces generated by the hydraulic actuators are applied axially and synchronously on the members of the joint.

There are five hydraulic loading actuators: a main cylinder and four branch cylinders. The main cylinder is fixed at the top, whose axis coincides with the vertical axis of the spherical structure. Two branch cylinders are placed on the upper vertical curved rails, and the other two are placed on the lower ones. Each cylinder is optional for a specific static test according to the actual loading requirements of the specimen; e.g., the main cylinder can be unavailable for a specimen without the upper vertically axial member shown in Fig. 3. One end of each vertical rail lies on the horizontal rail embedded into the episphere of the frame. The other end is attached to the outer ring of the slewing bearing. The inner rings of the slewing bearings are fastened to the foundation.

As shown in Fig. 3, the position of the branch cylinder can be represented by (r, θ, ϕ) under the spherical coordinate system, where r is radial distance, θ the polar angle, and ϕ the azimuth angle. The polar angle of the branch cylinder θ can be regulated by rotating the vertical rail around the vertical axis of the spherical structure. Its azimuth angle ϕ can be also adjusted since the branch cylinder is capable of moving along the vertical rail and rotating around the center of the spherical structure. The centers of the vertical and horizontal rails are consistent with the sphere center, so r remains constant when the branch cylinder rotates. In addition, the loading cylinders can be replaced by other restraints, such as fixed supports, spherical hinges and revolute pairs. Meanwhile, additional hydraulic actuators can be attached to the spherical structure to apply extra loading forces to the tested specimen.

From the review in Section 1, the design criteria of the proposed apparatus can be drawn as follows:

1) Large force: Although the ultimate load test of a small-scale model is usually used to study the mechanical behavior of truss structures [19], it cannot simulate the property effect caused by local deformation or welded joints. Thus the maximum loading forces are selected as large as possible to fulfill the test requirements of most truss joints. Then the spherical structure is designed in detail to be able to withstand the specific forces. The deformation of the spherical frame can be neglected in contrast to that of the specimen, which means that enough stiffness of the spherical frame can be ensured. Besides, the frame is sufficiently strong to avoid structural damage even if the maximum loading forces are exerted on the specimen.
2) High universality: There are some dead zones at the top and bottom of the sphere where the branch cylinder cannot reach, since it can only move along the vertical rail. Due to the dimensions of the hydraulic cylinder and the positioning mechanism, there is an inevitable angle difference between the directions of two loading forces generated by adjacent cylinders. The dead zones of force directions should be minimized consequently to enable the apparatus suitable for testing more types of truss joints. Therefore the mechanical components in the spherical frame, including the vertical rail, the branch cylinder, and their drive modules, should be designed as compact as possible. Otherwise the actuators cannot be positioned at the desired place, since their motion could interfere with each other.
3) High automaticity: The positioning assignments of the hydraulic actuators and the loading tests should be carried out by the control systems to improve the testing efficiency. The positioning accuracy of the actuators should be ensured, aiming at reducing the potential hazard of unbalance loading.

Based on the criteria above, the proposed apparatus was designed in detail and fabricated in the Structural Laboratory, Zhejiang University. The mechanical system and the control system are introduced as below.