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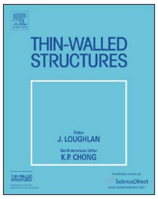

Full length article

# Dynamic behaviour and seismic design method of a single-layer reticulated shell with semi-rigid joints

Huihuan Ma[a,*], Zhiwei Shan[b], Feng Fan[a]

[a] School of Civil Engineering, Harbin Institute of Technology, 202 Haihe Road, Nangang District, Harbin 150090, PR China
[b] School of Civil Engineering, The University of Hong Kong, Hong Kong, PR China

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ABSTRACT

Most of the existing studies on reticulated shells with a semi-rigid joint system have been focused on the mechanical properties under static loads. Taking material and geometric nonlinearities into account, the finite element analysis (FEA) model of a single-layer reticulated shell with semi-rigid joints was established using the software ABAQUS and then validated through comparison with the experimental result. Based on the bending stiffness of a bolt-column (BC) joint obtained through experiments, the dynamic behaviour and a seismic design method for single-layer reticulated shells with semi-rigid joints were investigated in this paper. First, analysis of the free vibration frequency of the single-layer latticed domes with semi-rigid bolt-column (BC) joints was conducted based on several different parameters, including joint stiffness, ratio of rise to span, initial geometric imperfection. Second, the seismic internal force coefficient of the members of the semi-rigidly jointed spherical single-layer reticulated shells of different parameters was studied in detail. Finally, the seismic internal force coefficients for spherical single-layer reticulated shells with semi-rigid joints under a common earthquake were derived.

## 1. Introduction

Single-layer reticulated shells are well known to tend to be unstable under dynamic working actions. With large-span space structures, such as exhibition halls, stadiums and railway stations, being increasingly used in public facilities in recent years, reticulated shells have attracted more attention. The seismic performance of a reticulated dome not only is directly related to the safety of a building but also has a huge impact on the socio-economic development and the security of people. Therefore, researchers around the world have made great efforts to address the issues, such as the dynamic response and failure mechanism of these structures subjected to dynamic loads. However, most of the studies on the dynamic behaviour of a single-layer reticulated shell assume that the connections behave as perfect rigid joints, such as the dynamic performances and failure characteristics of single-layer reticulated domes subjected to an earthquake discussed in [1] as well as the study performed on the seismic performance of a single-layer reticulated dome [2,3].

However, the joints in most space structures are semi-rigid, for example the MERO joint systems [4–6], the aluminium alloy truss connector [7], the socket joint system [8] and the bolt-column joint system [9]. Single-layer reticulated shells with the above-described semi-rigid joints can provide a good solution for small- and medium-span space structures because of their rapid construction speed, high fabrication accuracy and beautiful appearance. Therefore, interest in single-layer spatial structures has grown significantly in the recent years. Observations from an earlier study [4,10] confirmed that connection stiffness had a significant effect on the load-displacement behaviour of a single-layer spatial structure. Aitziber et al. [11,12], Ma et al. [13,14], Fan et al. [15] and Kato et al. [16] verified that the rigidity of joints is an important factor that influences the behaviour of a single-layer latticed shell. However, those research studies primarily focus on the study of the mechanical properties of single-layer latticed shells with semi-rigid joint under static loads.

Few investigations on the dynamic behaviour of a single-layer latticed shell with a semi-rigid joint have been conducted. Hence, it is worthwhile to explore dynamic mechanical performance of a single-layer latticed shell with a semi-rigid joint.

In this paper, finite element models of single-layer reticulated shells with the semi-rigid bolt-column joints are established. The rules of free vibration frequency are explored, considering the joint stiffness, ratio of rise to span, section of members, span and initial geometric imperfection. Under a common earthquake, seismic internal force coefficients of the single-layer latticed shell with different stiffness are derived for

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* Corresponding author.
*E-mail addresses:* mahuihuan@hit.edu.cn (H. Ma), shanzw@foxmail.com (Z. Shan).

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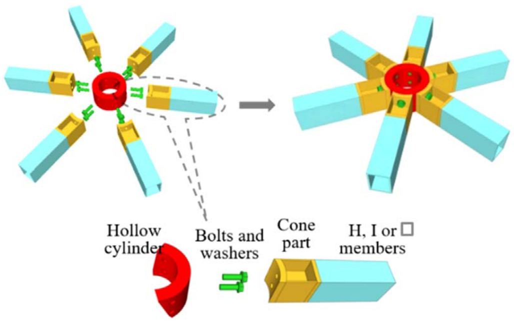

**Fig. 1.** Bolt-column joint.

seismic design.

## 2. The semi-rigid bolt-column (BC) joints

The bolt-column joint is composed of a hollow cylinder, high-strength bolts, washers, and end-cone part, as shown in Fig. 1. It can be used to connect H, I, or rectangular members in the real structures.

The end-cone part consists of five plates, which are welded at both ends of the members in the factory. At the construction site, the two high-strength bolts are used to connect the members to the column node without any welding work. All holes in the hollow column are tapped to accommodate the threaded part of the bolts. The two high-strength bolts are screwed into the hollow column node from the end-cone part. One concave washer is employed at each bolted connection; they are placed at the outside of the column node. The washers smoothly transmit axial compressive or tensile force. The high competitiveness of the joining technologies is related to the high bending stiffness, easy assembly, machining reduction, and high speed of construction.

As mentioned in [17], the BC joint system exhibits an adequate bending stiffness and bending capacity. The response of the connection embodies typical elasto-plastic behaviour under a bending moment. To obtain the whole moment-rotation curves of the joints, the experiment was performed on the joints with M24 (bolt diameter of 24 mm) and M27 (bolt diameter of 27 mm) high-strength bolts [17]. The test setup is shown in Fig. 2. The instrument arrangement and typology were considered to evaluate the main characteristics of the semi-rigid joints (stiffness, strength, rotation behaviour, and failure mode). The bottom plate of the specimen was employed to fix the specimen on the rigid frame; it is welded to the support beam to prevent slippage. The bending moment at the joint can be applied via the horizontal hydraulic jack. The connection rotation can be calculated based on the level displacements at points P1-P3, which are obtained by the LVDTs.

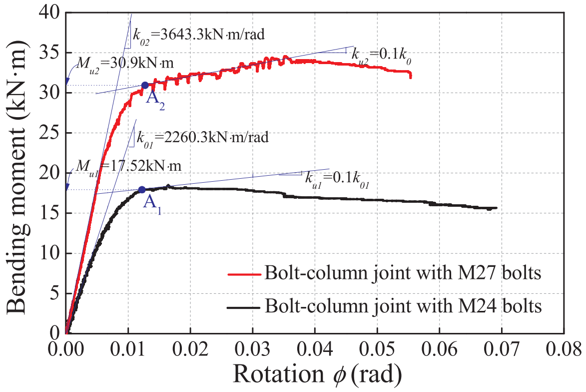

**Fig. 3.** Moment -rotation curves of the bolt-column joints [17].

The moment-rotation curves of the bolt-column joints obtained from the experiments are plotted in Fig. 3. In the figure, $k_O$ is the initial bending stiffness of the joints; $k_u$ is the post-limit stiffness of the joints, which is defined as 10% of the initial stiffness, $k_O$; $M_u$ is the plastic moment resistance of the joints, which corresponds to the point A of the regression line obtained for the post-limit ($k_u$) stiffness.

The bolt-column joints exhibit an adequate bending stiffness and bending capacity. The response of the connection exhibits linear behaviour in the early loading sequence and subsequent nonlinearity, which embodies typical elasto-plastic behaviour. The results indicate that the initial bending stiffness $k_O$ of M27 BC joints is much higher than the initial bending stiffness of M24 BC joints. The plastic moment resistance $M_u$ also improved when the diameters of the high-strength bolts increase. Therefore, the effect of the diameters of the bolts on the mechanical behaviour of the BC joint is significant.

## 3. The numerical model of single-layer reticulated shells with semi-rigid joints

Based on the moment-rotation curve of the bolt-column joints obtained from the experiment, the finite element models of single-layer reticulated shells with semi-rigid joint were built.

### 3.1. The member model

The member model is the basic element in the semi-rigid jointed reticulated shells. The member model in this paper is established in the software ABAQUS as shown in Fig. 4.

The member model in Fig. 4 consists of three main parts: joint

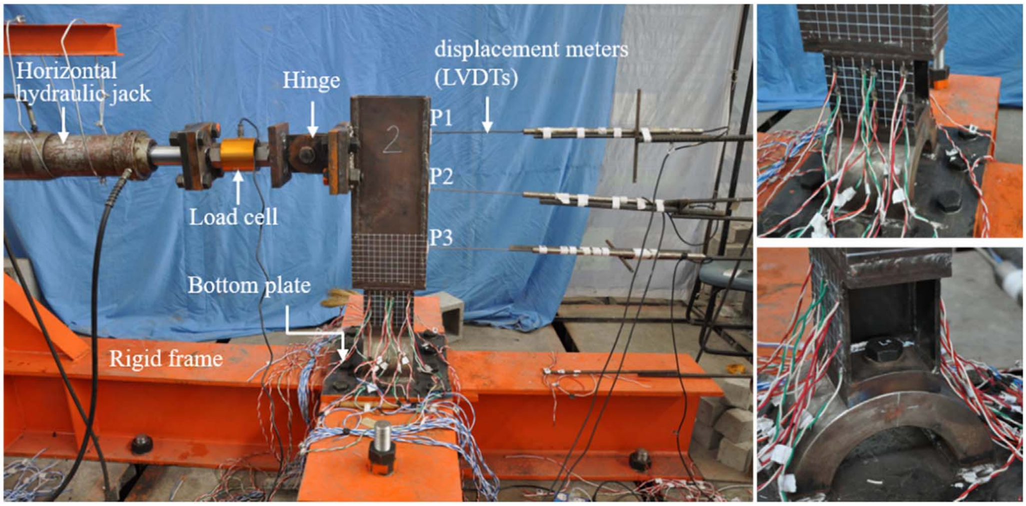

**Fig. 2.** Picture of the test setup.