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Investigations on the mechanical behavior of suspend-dome with semirigid joints

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ABSTRACT

Most finite element models of actual projects developed using general finite element software are rigid or hinge connected. These models are inconsistent with the actual situations of most actual projects that are semirigid jointed. The double element method was adopted to estimate the influence of joint stiffness on the mechanical behavior of suspend-dome structures. First, the accuracy of this method was validated. This approach was adopted to analyze the influence of joint stiffness on the mechanical behavior of the overall structure. Buckling, modal, and dynamic response analyses were conducted. The effect of joint stiffness on the buckling capacity of suspend-dome and single-layer latticed shell was derived and compared. The influence of joint stiffness on the characteristics of natural vibration was also determined. Finally, seismic response analysis was conducted to estimate the influence of joint stiffness on structural dynamic response. Results indicate that rigid connected finite element models may be unreliable to calculate dynamic response during the design phase.

1. Introduction

Suspend-dome is a new style of space-reticulated structure, which is formed by combining a single-layer reticulated shell and cable–strut system. Compared with traditional single-layer reticulated shell structures, suspend-domes exhibit a more uniform spatial stiffness distribution, has less thrust on supports, and shows a stronger spanning capacity [1].

Researchers examined the performance of the suspend-dome structure from the experimental and numerical viewpoints [2,3,4,5,6]. Current research demonstrate that the buckling capacity of the pin-connected suspend-dome is lower compared with that of the rigidly connected suspend-dome [7]. However, the influence of joint stiffness has not been quantitatively verified.

The upper latticed shells usually consist of thousands of components that are connected by joints. The stiffness of connections was determined to be one of the factors that significantly affect the behavior of space structures, and these effects were investigated numerically and experimentally [8,9]. In the actual design process, the joints are assumed to be either pinned or rigid joints. This assumption may result in a significant deviation from the actual condition. Lattice shells with semirigid joints can provide a good solution for space structures. Thus, including joint stiffness in the numerical model is necessary.

Predicting the mechanical behavior of joints is the first step in analyzing spatial structures with semirigid joints. Many studies were conducted to analyze the mechanical behavior of joints in space structures [10]. López et al. [11,12], Ma et al. [13], Fan et al. [14], and Kato et al. [15] verified that the rigidity of joints is an important factor that influences the behavior of a single-layer latticed dome. Fan [8,16,17,18] systematically conducted experimental and numerical analyses to investigate the influence of joint stiffness on the mechanical behavior of latticed shells. Finite element method and experimentation were the main approaches to examine semirigid joints [19].

However, the studies mainly discuss the joints itself or simple structures, such as steel frames [20,21,22,23,24,25]. The axial direction, length, and cross section of the spatial latticed structures, which consist of thousands of components, significantly vary. Establishing numerical models that consider the influence of joint stiffness is time-consuming and tedious. A few of these numerical reticulated shell models were used because they are complex and relevant studies are limited. A convenient and efficient method that integrates joint stiffness in numerical models of spatial latticed structures has not yet been developed. In this study, double element method was adopted to investigate the influence of joint stiffness on the mechanical behavior of the suspend-dome.

2. Double element method

Research on the stiffness of joints and their effects on the behavior of structures has been an area of interest to engineers and scientists in recent years, and many applicable conclusions have been achieved.

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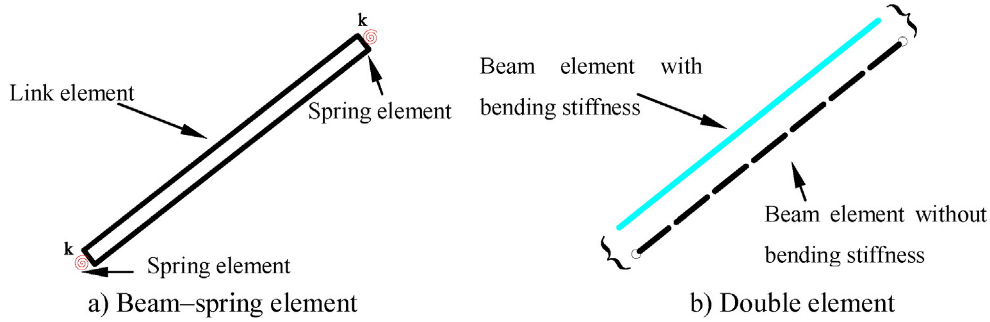

Fig. 1. Numerical model considering joint stiffness.

However, no applicable method that considers joint stiffness in a general finite element software has been developed. A simplified method integrating joint stiffness was proposed in this study.

This method assumes that every component of a latticed shell is composed of two elements, namely, beam element with only bending stiffness and beam element without bending stiffness.

The rotation angle of the beam under action of moment M, as shown in Fig. 2, can be calculated using Eq. (1) for a beam with a constant cross section. The bending stiffness of the beam can be represented by Eq. (2).

The significant influence of the stiffness of joints on the mechanical performance of lattice shells has been validated [16], particularly for buckling behavior. In a numerical model, the joints of latticed shells were assumed to be a rigid or simple joint. In fact, almost all joints in structures exhibit some degree of semirigid behavior. For these kinds of structures, the stiffness of action of joints can be substituted by spring element [18], as indicated in Fig. 1(a). The rotation angle of this system under the action of moment M can be calculated through Eq. (3). The bending stiffness of the beam can be represented by Eq. (4), through which it can be concluded that, when the joint stiffness k was equivalent to Eq. (2), it is sufficiently large.

López [21] proposed the use of an elasto-plastic cylinder located between the tube and the balls to simulate the bolt, which is time-consuming and work-intensive to establish the numerical models of latticed shells because of the large amount of components. This study proposed the double element method to consider joint stiffness, as shown in Fig. 1(b). That is, each component of latticed shells is composed of two elements, namely, beam element with bending stiffness of the component and beam element without bending stiffness.

$$\theta = \int_l \frac{M}{EI} \mathrm{d}l = \frac{Ml}{EI}, \tag{1}$$

$$\frac{M}{\theta} = \frac{EI}{l}, \tag{2}$$

$$\theta = \int_l \frac{M}{EI} \mathrm{d}l + 2 \times \frac{M}{K} = M\left(\frac{l}{EI} + \frac{2}{K}\right), \tag{3}$$

$$\frac{M}{\theta} = \frac{1}{\frac{l}{EI} + \frac{2}{K}} = \frac{EI}{l} \times \frac{K}{K + \frac{2EI}{l}}, \tag{4}$$

where θ is the rotation angle of the beam, I is the moment of inertia of the members, $E = 206$ GPa represents Young's modulus, and K is the bending stiffness of the spring element.

We assume that α indicates the overall bending stiffness factor of the beam element and β indicates the bending stiffness factor that only considers the joint bending stiffness, as shown in Eqs. (5) and (6). Eq. (7) denotes the relationship between α and β. Fig. 3 indicates the curves between α and β. The overall bending stiffness factor tends to 1 with the increase in β.

$$\alpha = \frac{K}{K + \frac{2EI}{l}}, \tag{5}$$

$$\beta = \frac{K}{\frac{EI}{l}}, \tag{6}$$

$$\alpha = \frac{\beta}{\beta + 2}. \tag{7}$$

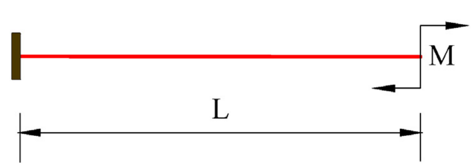

Fig. 2. Beam under the action of moment.

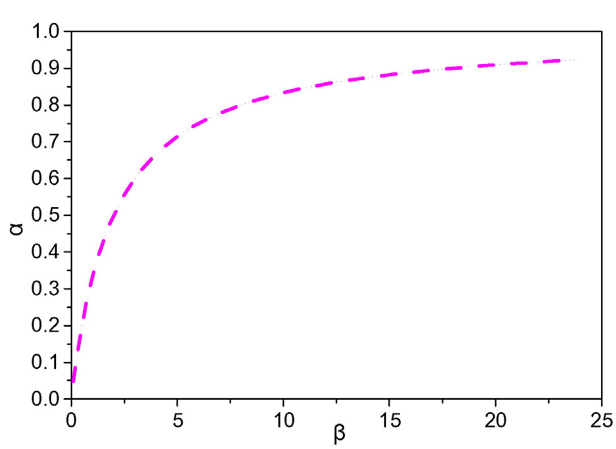

Fig. 3. Curves between α and β.

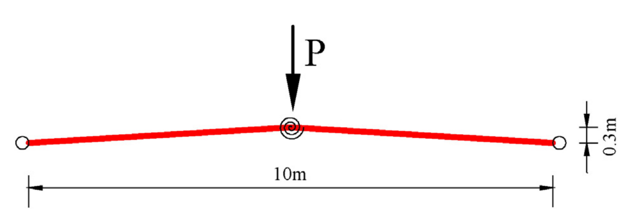

Fig. 4. Two-member structure with semirigid joint.