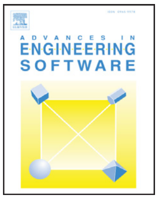
Advances in Engineering Software 000 (2017) 1–7

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft



Research paper

Novel numerical method for the analysis of semi-rigid jointed lattice shell structures considering plasticity

Zhongwei Zhao[a,b,*], Haiqing Liu[a], Bing Liang[a]

[a] *School of Civil Engineering, Liaoning Technical University, Fuxin 123000, China*
[b] *Department of Civil Engineering, Tianjin University, Tianjin, 300072, China*

ARTICLE INFO

Article history:
Received 1 March 2017
Revised 5 June 2017
Accepted 17 July 2017
Available online xxx

Keywords:
Bending stiffness
Joint axial stiffness
Inelastic analysis
Buckling behavior
Semi-rigid joints
Double element method

ABSTRACT

The joint bending and axial stiffness significantly influence the mechanical performance of lattice shell structures. However, most finite element models of the actual project established in the general finite element software are rigid or hinge-connected for simplicity. These characteristics are inconsistent with the actual situation and may lead to a large error. A novel numerical method was proposed in this paper to estimate the influence of joint stiffness, which includes bending and axial stiffness, on the mechanical behavior of lattice shell structures. This method can be used for inelastic analysis. First, the accuracy of the proposed element model was validated. The model was used to analyze lattice shell structures. The proposed element model can simultaneously consider semi-rigid joints and inelasticity with high accuracy, and it can be conveniently constructed in general finite element software.

1. Introduction

The design and analysis of single-layer lattice shells are usually based on the assumption that the connections behave as pinned or rigid joints. However, most joints are semi-rigid. Single-layer lattice shells with semi-rigid joints behave quite differently from those connected by rigid joints [1].

A number of researchers have investigated the performance of lattice shell structures based on experimental and numerical methods [2–6]. Studies have shown that the buckling capacity of the pin-connected lattice shell structure is lower compared with that of the rigidly connected lattice shell structure [7]. Liu [8] presented a stability analysis method, which can consider structural imperfection, member initial curvature, semi-rigid joint, and skin effect to study the stability behavior of aluminum dome structures.

Numerous studies on the mechanical behavior of joints in space structures have been conducted. López et al. [9,10], Ma et al. [11], Fan et al. [12], and Kato et al. [13] have verified that the rigidity of joints influences the behavior of a single-layer lattice dome. Fan [14–16] systematically conducted experimental and numerical analyses to investigate the influence of joint stiffness on the mechanical behavior of latticed shells. Guo [17] investigated the semi-rigid behavior of aluminum alloy gusset joints. Dabaon [18] conducted experimental work to study the behavior of space steel and composite semi-rigid joints. Dubina [19] evaluated the semi-rigid behavior of some typically bolted connections. Larsen [20] studied the semi-rigidity of joints on the behavior of timber structures. Urbonas [21] presented an analysis of semi-rigid beam-to-beam end-plate bolted joints subjected to bending and tension or a compression axial force. Shi [22] investigated the rotational stiffness, critical sections, and failure modes of a novel cast aluminum joint. The aforementioned studies indicate that the behavior of joints plays an important role in structural behavior and should be considered in the design process for lattice shells. Zuo [23] exploited a semi-rigid beam element (SRBE) that consists of a beam element with two semi-rigid connections at the ends to simulate the flexibility of joint.

The inelasticity of semi-rigid joint has been studied by a number of researchers [24]. Afsin [25] proposed a macro-element model with the inelasticity spread and the localized nonlinear semi-rigid hinges; however, this method requires complex programming work and is unsuitable for spatial structures.

Many researchers have investigated the influence of joint bending stiffness on mechanical behavior; however, studies on joint axial stiffness remain scarce. The cross section of connection is usually not the same as a component's section; thus, joint axial stiffness is not the same as a component; an example is the ORTZ system [10]. Ma [26] investigated the mechanical behavior of the socket joint system subjected to bending with and without axial force, but only bending stiffness was explored in this study. Thai [27], Nguyen [28], and Razavi [29] proposed numerical methods to

---

[*] Corresponding author at: School of Civil Engineering, Liaoning Technical University, Fuxin 123000, China.
E-mail address: zwzhao@yeah.net (Z. Zhao).

http://dx.doi.org/10.1016/j.advengsoft.2017.07.005
0965-9978/

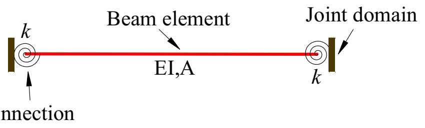
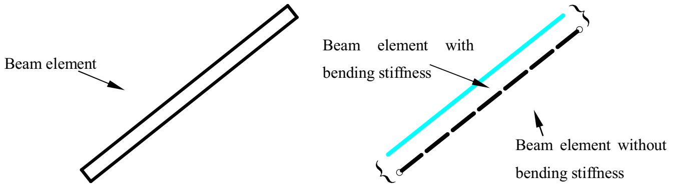


Fig. 1. Mechanical model of the components in latticed shells.

consider inelasticity for frame structures. Mohammad [30,31] investigated the interaction of the axial force–bending moment in a jointing system.

The axial direction, length, and cross section of the spatial lattice structures, which consist of thousands of components, significantly differ from each other. Establishing numerical models that consider the influence of joints stiffness is time-consuming and tedious. Few numerical reticulated shell models are used because their performance is complex, and relevant studies are limited. Moreover, the real constant of nonlinear spring element should be set according to experimental work to include the mechanical behavior of joint after yielding. Thus, based on the study background, a novel numerical method was proposed to consider joint bending stiffness and joint axial stiffness. This work is also improved as the method can be adopted for inelastic analysis.



a) General beam element b) Double-element

Fig. 2. Numerical model considering joints stiffness.

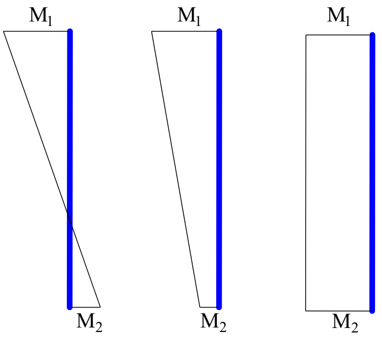


Fig. 3. Bending moment diagram of the component.

2. Mechanical model of components

Latticed shell structures are comprised of thousands of components. The joints of single layer latticed shells are rigidly or hinge-connected during the design phase. However, the studies mentioned above indicated that most components are semi-rigidly connected. The stiffness of joints significantly influences the mechanical performance of lattice shells.

The joint can be replaced with torsional and bending spring in a mechanical sense when the joint stiffness is considered, as shown in Fig. 1. Joint domain indicates joint core, whose deformation can be neglected owing to large stiffness. k indicates joint stiffness. In the existing studies on semi-rigid joints, linear elastic rotational springs [32,33] or nonlinear spring elements [34–37] are adopted to simulate joint actions, especially in the numerical analysis of frame structures. However, this method is unsuitable for the analysis of spatial lattice shell structures owing to the thousands of components that always comprise the spatial lattice shell structures. Moreover, the coordinate system of each component at one joint is different. Thus, simulating the joint as spring is almost impossible.

3. Double element

Recently, engineers and scientists have been interested on the research of the stiffness of joints and their effects on the behavior of structures, and many applicable conclusions are achieved. However, there is no applicable method that considers joint stiffness in the general finite element software. A simplified method that considers joint stiffness is proposed in this paper.

This method assumed that every component of the latticed shell is composed of two elements: beam elements with only bending stiffness and without bending stiffness.

The stiffness of joints significantly influence the mechanical performance of latticed shells [14], especially the buckling behavior. In the numerical model, the joints of latticed shells are assumed as either rigid or simple. Almost all joints in the structures exhibit some degree of semi-rigid behavior. The action of joints stiffness for these kinds of structures can be substituted by spring elements [16].

López [10] proposed that an elastoplastic cylinder located between the tube and the balls simulates the bolt, which is inefficient and work-intensive when establishing the numerical models of latticed shells because of the numerous components. This paper proposed the double-element method to consider joints stiffness, as shown in Fig. 2b. Each component of latticed shells is composed of two beam elements, one with bending stiffness and the other without.

The general finite element software ANSYS was used to obtain load versus the displacement curves of structures. The two-member structure was initially established by an ordinary beam element (Beam 4) in ANSYS. BEAM4 is a uniaxial element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes [39]. The beam element in the double-element contains only bending stiffness and can be adjusted easily to consider the influence of joint stiffness [40–42].

4. Element for elastic-plastic analysis (EEPA)

4.1. Establishing of element for the elastic-plastic analysis

Given that the components in spatial lattice shell structures do not suffer midspan load, the max bending moment occurs at either end of the component. The bending moment diagram of the component in spatial lattice shell structures is shown in Fig. 3. Therefore, plasticity occurs at either end of the component during the loading process, which differs from the components in the frame structures. Thus, the influence of plasticity can be considered when the inelastic beam element is located at both ends of the components.

The EEPA is proposed in this paper to include the plasticity in the numerical model. The plasticity and the semi-rigid joint can be considered using this kind of element. The element has three parts: inelastic beam elements at both ends of the component and double element at the middle part of the component. The inelastic beam element indicates the joint, and the double element denotes the component, as shown in Fig. 4. The length of each part is also shown in Fig. 4.

The axial and bending stiffness of the joint are k_a and k_b, respectively, as shown in Fig. 5a. The length of the joint in the

Please cite this article as: Z. Zhao et al., Novel numerical method for the analysis of semi-rigid jointed lattice shell structures considering plasticity, Advances in Engineering Software (2017), http://dx.doi.org/10.1016/j.advengsoft.2017.07.005