Advanced Steel Construction – Vol. 15 No. 1 (2019) 93–99
DOI:10.18057/IJASC.2019.15.1.12

INFLUENCE OF RANDOM GEOMETRICAL IMPERFECTION ON THE STABILITY OF SINGLE-LAYER RETICULATED DOMES WITH SEMI-RIGID CONNECTION

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ABSTRACT

Single-layer reticulated domes are commonly used structural layouts due to their large span capacity and novel appearance. Such structures contain a large number of members, which inevitably lead to imperfection. In this study, a numerical method considering the initial curvature of members, nodal installation error, and joint stiffness was proposed. The randomness of the initial curvature direction, initial curvature magnitude, and joint stiffness could be considered simultaneously. The influence of random geometrical imperfection on the stability of two types of latticed shell structures was investigated. The proposed method could be performed based on general finite element software, and its applicability could be ensured.

ARTICLE HISTORY

Received: 20 July 2017
Revised: 1 January 2018
Accepted: 29 January 2018

KEYWORDS

Member initial curvature;
Nodal installation error;
Latticed shell structure;
Buckling capacity;
Semi-rigid connection

1. Introduction

Single-layer reticulated domes are commonly used structural layouts due to their large span capacity and novel appearance. Such structures usually contain hundreds of members and joints, which inevitably lead to imperfections, such as lack of fit [1].

In most analyses, members in latticed shells are assumed to be perfectly straight. However, the imperfection of structural members is inevitable, which may cause negative influence on the structural mechanic performance [2]. In view of the combined influence of shear deformation and member imperfection, Li and Liu [3] developed an accurate beam element stiffness matrix for the nonlinear analysis of planar steel frames. Adman and Afra [4] obtained an accurate displacement shape function for beam elements with imperfection under any boundary conditions. López et al. [5] indicated that the rigidity of joint requires further study because it significantly affects the behavior of the structures. Chan [6-13] conducted a systematical nonlinear analysis on semi-rigid steel frames. The use of stability functions that allow initial imperfections in place of cubic Hermite element was proposed to conduct the second-order analysis for the design of glass-supporting and pre-tensioned trusses [6]. In the analysis, the member was assumed to be pinned or rigidly connected. However, semi-rigid connection and installation error cannot be considered simultaneously.

Producing a precise single-layer assembly of reticulated domes is virtually impossible. Initial curvature and nodal installation error are the most common geometrical imperfection for latticed shell structures. In this regard, several investigations have been conducted [14-17], each include one or several random variables.

El-sheikh [18] investigated the effect of geometric imperfections on the capacity and failure mechanism of single-layer barrel vaults, and presented that geometrical imperfections decrease the load bearing capacity. Zhao et al. [19] investigated the effects of random geometrical imperfections on concentrically braced frames. Kato et al. [20] discussed buckling collapse and its analytical method of steel reticulated domes with semi-rigid ball joints. Spring element was adopted to simulate semi-rigid joints, and four types of geometrical imperfections were studied. The magnitude of maximum nodal imperfection was set to 50 mm and 100 mm. Bruno et al. [21] investigated the sensitivity of the global and local stability of a hybrid single-layer grid shell to a set of equivalent geometric nodal imperfections, which represents the actual structure and construction imperfections.

In the present work, a numerical method considering member initial curvature, nodal installation error, and joint stiffness was proposed. The influence of random geometrical imperfection on the stability of two types of latticed shell structures was investigated. The proposed method could be executed based on general finite element software, and its applicability could be ensured.

2. Establishment of random geometrical imperfection

2.1. Establishment of initial member curvature

General finite element software ANSYS was used to establish imperfect elements. In traditional analysis, straight line was generated and meshed to simulate the components of the latticed shell. Member imperfection cannot be considered in this case. In this study, a straight line was replaced by a curved line through “BSPLIN” command. The magnitude of imperfection was set in the middle of the component. In most analysis, the imperfection is deemed to be of a half-wave sinusoid, which can be achieved by adding an imperfection value at other points to make the b-spline close to the half-wave sinusoid, as shown in Fig. 1. To set the imperfection value conveniently, a local coordinate system was set up. The x-axis is in the member direction, whereas the y-axis is in the vertical direction. Imperfection value can be generated by adopting the sine function in ANSYS. All imperfect members can be generated through looping statements. The entire process can be performed easily and is easy for engineers to master. The accuracy of this method had been validated in existing literature [22].

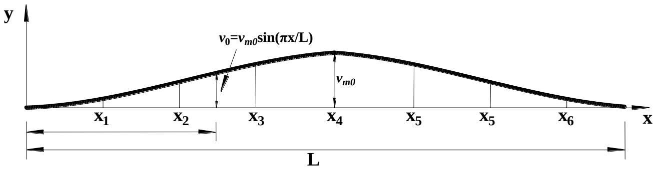


Fig. 1 Imperfection member and local coordinate system

The method of establishing imperfect members has not been considered in the randomness of imperfection direction. Thus, the method was developed in the present work. A random constant θ ranging from 0 Rad to 2π Rad was generated. The local coordinate system was generated according to nodes located at the two sides of components. Then, the local coordinate system was rotated around the *x*-axis. The random constant satisfied a uniform distribution. Then, the imperfection direction could be randomly distributed all throughout.

To incorporate the influence of joint stiffness, imperfect elements with semi-rigid joints were adopted in this study. Detailed information can be derived from existing literature [22-24]. Two types of latticed shell structures were analyzed.

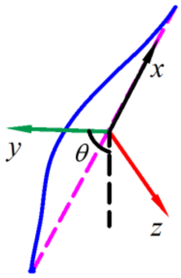


Fig. 2 Rotation of local coordinate system

2.2. Establishment of nodal installation error

Random parameters Δx, Δy, and Δz were introduced to represent nodal installation error. The magnitude of nodal installation error is $E_{max} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$. The random constants Δx, Δy, and Δz satisfy a uniform distribution. The value range of Δx, Δy, and Δz are ($-E_{max}$, E_{max}), ($-\Delta y = \sqrt{E_{max}^2 - \Delta x^2}$, $\Delta y = \sqrt{E_{max}^2 - \Delta x^2}$), and ($-\Delta z = \sqrt{E_{max}^2 - \Delta x^2 - \Delta y^2}$, $\Delta z = \sqrt{E_{max}^2 - \Delta x^2 - \Delta y^2}$). The nodal installation error was considered by adding random parameters to the nodal coordinate.

3. Analyzed structures

Schwedler and Kewitte domes with an increase of 0.1 of their span were analyzed to investigate the influence of geometrical imperfection on different types of reticulated structures. Two Kewitte domes were analyzed to investigate the influence of geometrical imperfection on the buckling capacity of Kewitte domes with different rise–span ratio, as shown in Figs. 3 and 4. The surface of the dome is in the shape of a sphere. The Young's modulus and yield strength are 2.1×10^5 MPa and 345 MPa, respectively.

In the analysis, loads were applied uniformly on the nodes of the dome, that is, 200 KN per node for the Schwedler and Kewitte domes. Every member was meshed by 20 elements. Parametric analysis was conducted to investigate the influence of the initial curvature and nodal installation error on the stability of different types of latticed shell structures.

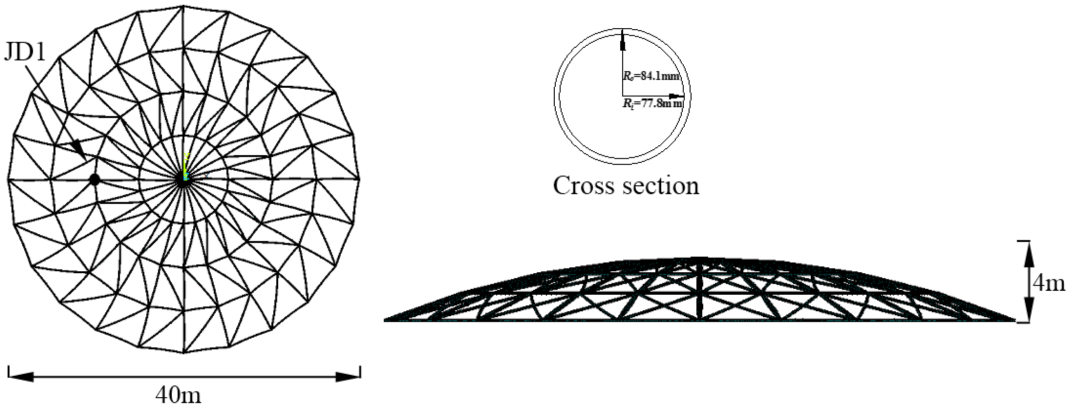
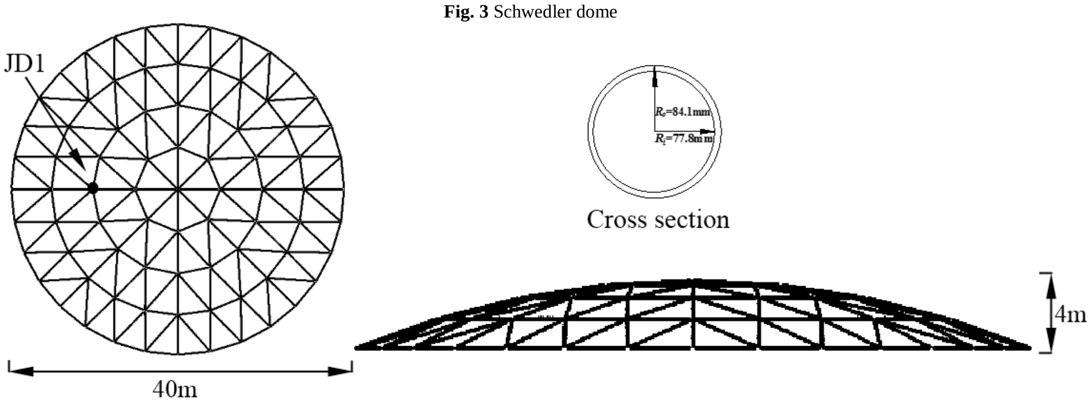
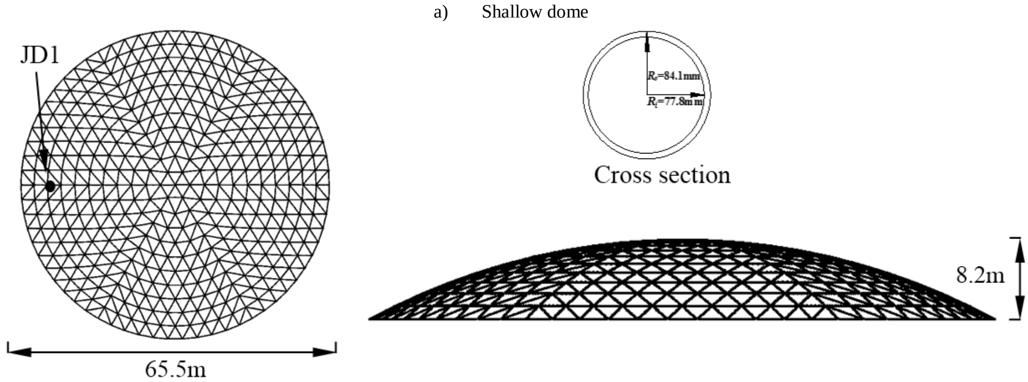


Fig. 3 Schwedler dome



a) Shallow dome



b) Deep dome

Fig. 4. Kewitte dome

4. Influence of member imperfection on stability

4.1. Influence of member imperfection amplitude

In this section, parametrical analysis was conducted on the influence of the magnitude of initial curvature (v_{m0}) on structural buckling capacity. A numerical model with v_{m0}=15*l*/1000 is shown in Fig. 5.

In view of the randomness of member imperfection, 100 computations were performed for each joint stiffness factor. v_{m0} was set as different values. The probabilistic model of v_{m0} satisfied a uniform distribution because only the variation range of the buckling load was considered.

Fig. 6 shows the influence of member imperfection on the buckling load factor of Schwedler latticed shell when the joint stiffness was set to different values. Generally, the buckling load capacity of the Schwedler latticed shell increases with the joint stiffness. The results show that when the joint stiffness was 0.1 and v_{m0} was l/1000, the buckling load factor of the ideal structure was 0.49. The buckling load factor of the defective structure changed from 0.29 to 0.49. When v_{m0} was set to 5l/1000, 10l/1000, and 15l/1000, the buckling load factor of the defective structure changed from 0.29 to 0.35, 0.28 to 0.33, and 0.27 to 0.29, respectively. In addition, the buckling load was insensitive to the variation of v_{m0} when the joint stiffness was set to 0.1. The shell could be assumed as pinned joint in this condition.

The buckling load factor of the ideal structure was 0.6 when the joint stiffness was 1.0 and v_{m0} was l/1000. The buckling load factor changed from 0.58 to 0.6. When v_{m0} was set to 5l/1000, 10l/1000, and 15l/1000, the buckling load factor changed from 0.55 to 0.6, 0.54 to 0.57, and 0.52 to 0.57, respectively. Buckling capacity decreased with the increase of v_{m0}, and the variation range of buckling load factor was almost not influenced by v_{m0}.

The influence of the initial curvature on the semi-rigid connected Schwedler latticed shell would change with the stiffness factor. The change tendency of the load factor of a defective structure along with joint stiffness factor was almost the same with that of the ideal structure.

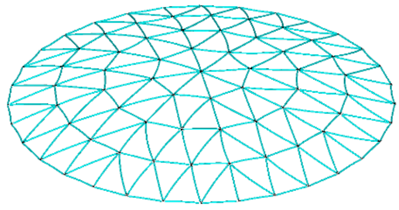
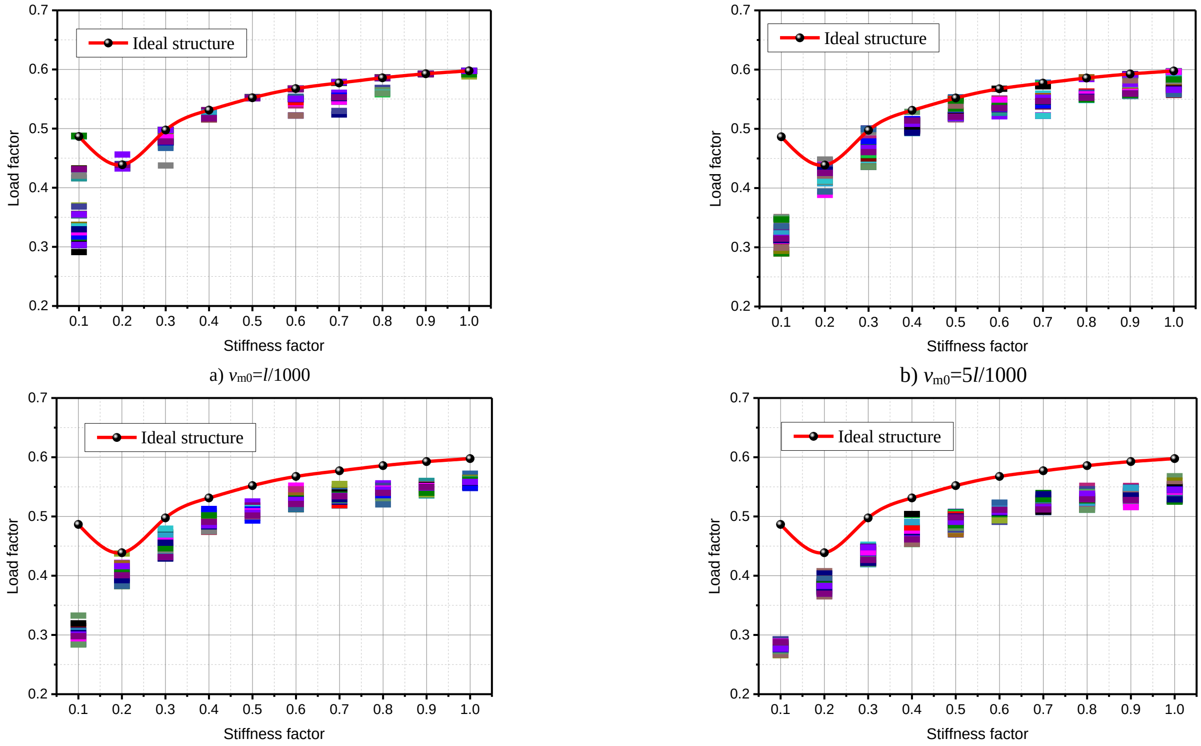


Fig. 5 Numerical model with v_{m0}=15l/1000



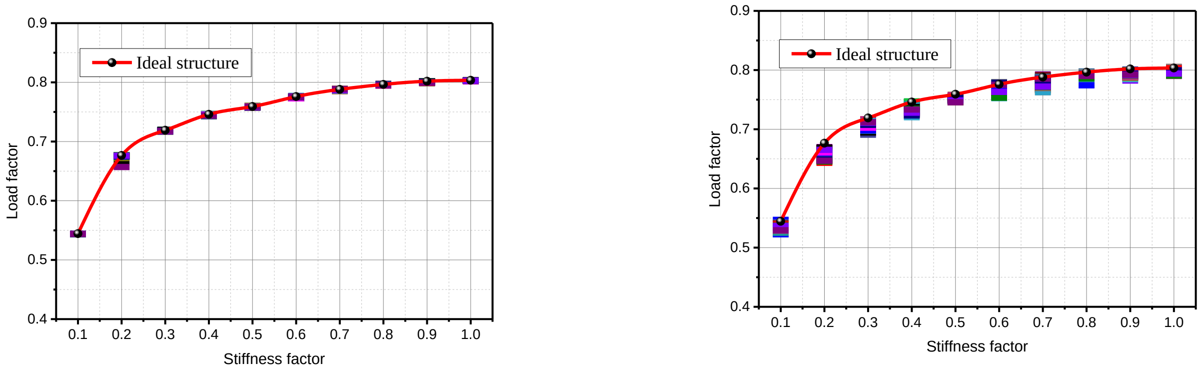
a) v_{m0}=l/1000 b) v_{m0}=5l/1000 c) v_{m0}=10l/1000 d) v_{m0}=15l/1000

Fig. 6 Influence of member imperfection on Schwedler latticed shell

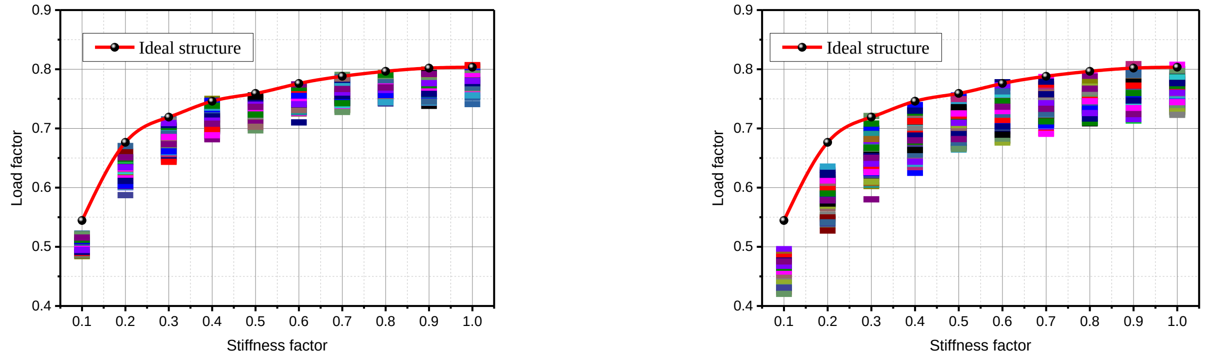
The changing rule of the buckling load of shallow K8 latticed shell along with joint stiffness factor and v_{m0} is shown in Fig. 7. The buckling load capacity was almost not influenced when v_{m0} was set to l/1000. The variation range of the buckling load factor increased with v_{m0}, and the peak value remained as the buckling load factor of the ideal structure, which was different from the Schwedler latticed shell.

The changing rule of the buckling load of deep K8 along with joint stiffness factor and v_{m0} is shown in Fig. 8. The variation range of the load factor of shallow K8 is larger than that of deep K8. This finding indicates that the sensitivity of the changing range of loading capacity to the initial curvature decreases with the increase of structural size.

The reduction factor indicated the ratio of the loading capacity derived from imperfect structures and the loading capacity derived from the ideal structure. The reduction factors derived by the shallow and deep K8 reticulated domes were compared. The change of the reduction factor along with the stiffness factor is shown in Fig. 9. The reduction factor was not closely related to the joint stiffness. A rule between the reduction factor and structure size was not established.

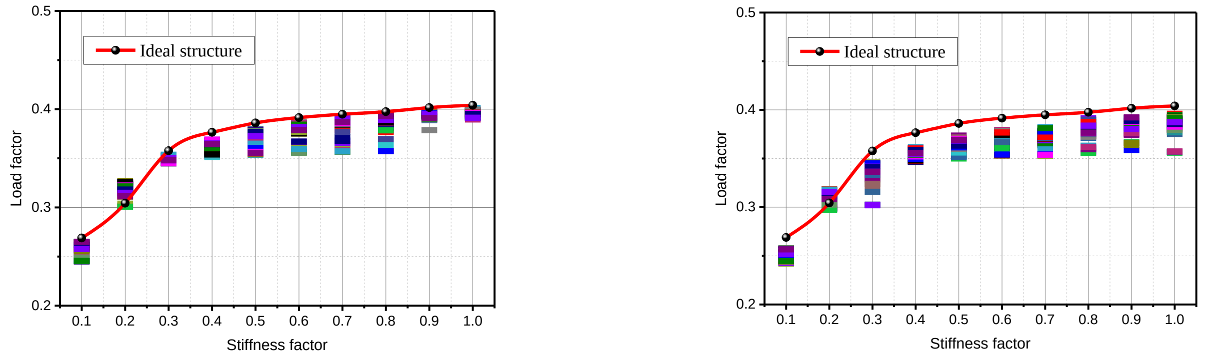


a) v_{m0}=l/1000 b) v_{m0}=5l/1000



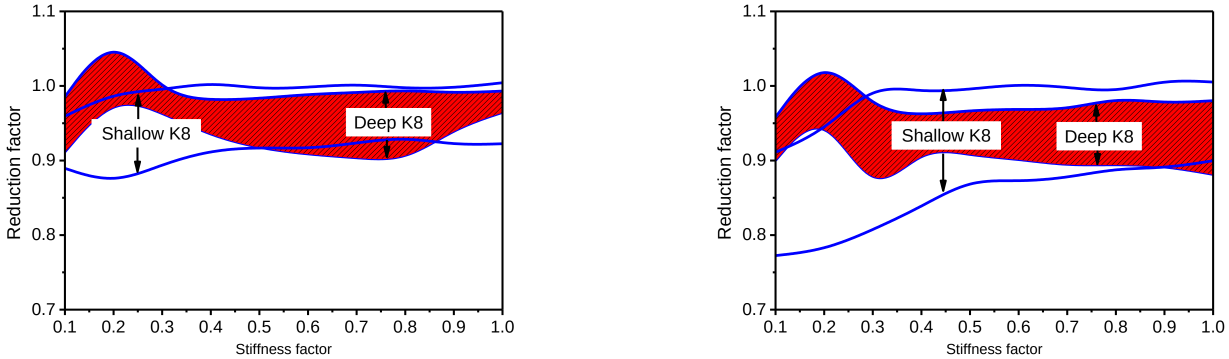
c) v_{m0}=10*l*/1000 d) v_{m0}=15*l*/1000

Fig. 7 Influence of member imperfection on shallow K8 latticed shell



a) v_{m0}=10*l*/1000 b) v_{m0}=15*l*/1000

Fig. 8 Influence of member imperfection on deep K8 latticed shell

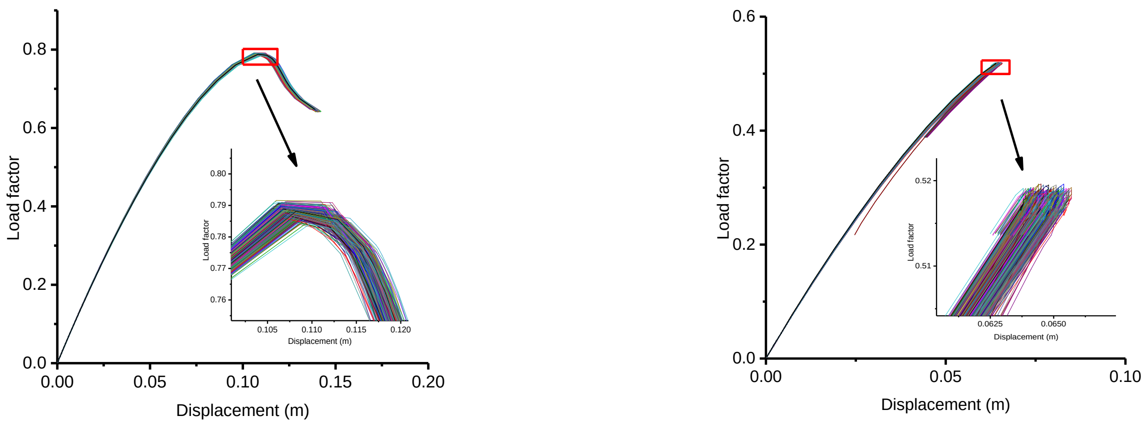


a) v_{m0}=10*l*/1000 b) v_{m0}=15*l*/1000

Fig. 9 Change of reduction factor along with stiffness factor (initial curvature)

4.2. Influence of initial curvature direction

Initial curvature may be in random direction in the actual project, and its direction may influence structural capacity. The influence of initial curvature direction is discussed in this section. The magnitude of initial curvature remained constant at *l*/1000 with joint stiffness of 0.1 and 1. The results in Fig. 10 indicate that the initial curvature direction almost has no influence on the structural buckling capacity when the joint stiffness factor was set to 0.1. The influence on structural buckling capacity remained within 1% when the joint stiffness factor was to 1.0. Thus, the influence of the initial curvature direction on K8 latticed shell could be neglected.



a) α=1.0 b) α=0.1

Fig. 10 Influence of initial curvature direction on shallow K8 latticed shell

5. Influence of nodal installation error on stability

Imperfections are determined using the eigenmode imperfection method in most of the numerical analysis of buckling capacity. However, this imperfection distribution mode was not consistent with the actual condition.

The nodal installation error was assumed to satisfy a uniform distribution in the present work. The magnitude of the nodal installation error (E_{max}) was set as different values. The numerical model with nodal installation error is shown in Fig. 11. The results are shown in Fig. 12.

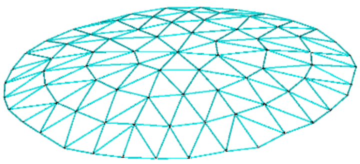


Fig. 11. Numerical model with E_{max}=400 mm

Fig. 12 shows the influence of nodal installation error on the buckling load factor of the Schwedler latticed shell when the joint stiffness was set as different values. Generally, the buckling load capacity of the Schwedler latticed shell increase with the joint stiffness. The results indicate that when the joint stiffness was 0.1 and E_{max}=15 mm, the buckling load factor of the ideal structure was 0.49. The buckling load factor of the defective structure changed from 0.24 to 0.3. When E_{max} was set to 45, 133, and 400 mm, the buckling load factor of the defective structure changed from 0.19 to 0.26, 0.13 to 0.25, and 0.1 to 0.25, respectively. In addition, the influence of nodal installation error on the buckling capacity of the Schwedler latticed shell was larger than that of the initial curvature. The variation ranges of the buckling load factor increased with the installation error E_{max}. The buckling capacity of the Schwedler latticed shell with nodal installation error was definitely lower than that of the ideal structure.

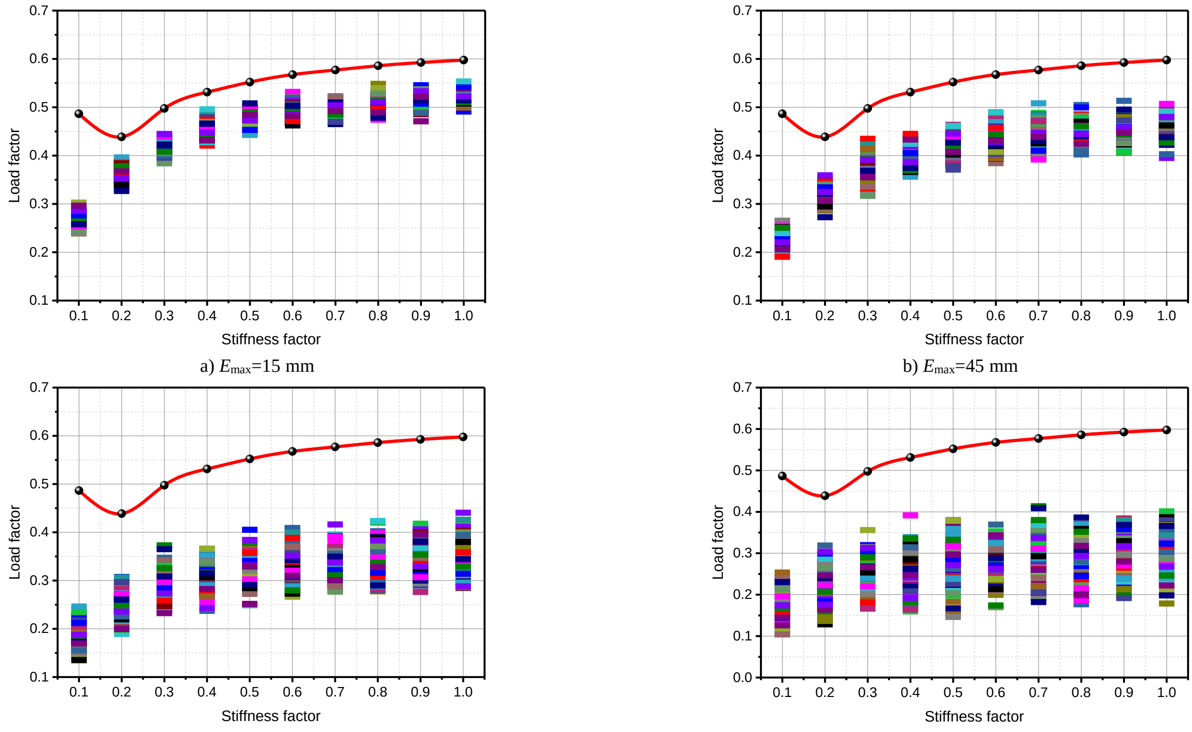
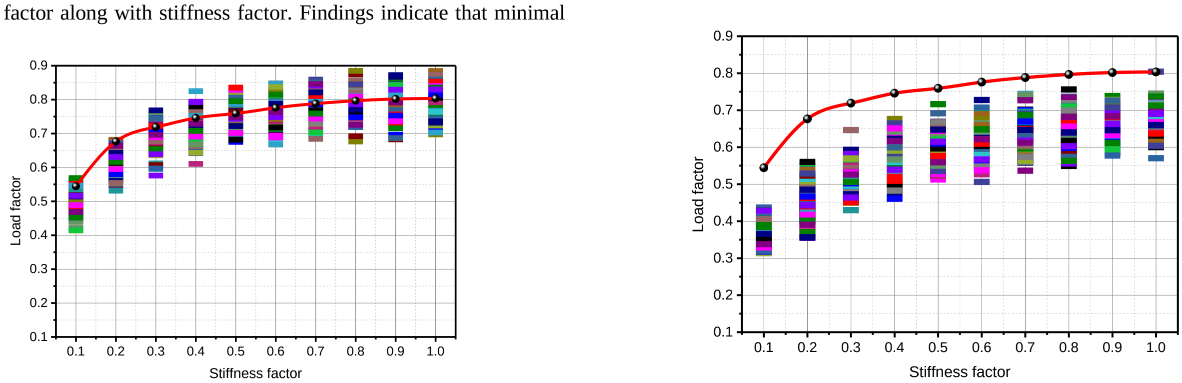


Fig. 12 Influence of installation error on Schwedler latticed shell

Fig. 13 shows the influence of nodal installation error on the buckling load factor of the shallow K8 latticed shell when the joint stiffness is set as different values. The results in Fig. 13(a) indicate that the buckling capacity of the shallow K8 latticed shell with nodal installation error may be larger than that of the ideal structure, which is different from the Schwedler latticed shell. The influence of nodal installation error on the K8 latticed shell was less than the Schwedler latticed shell.

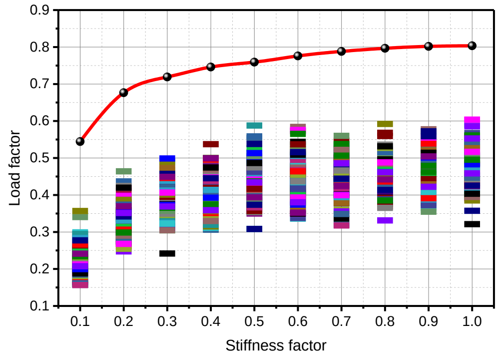
The influence of nodal installation error on the deep K8 latticed shell is depicted in Fig. 14. The results show that the changing range of the loading factor of the deep K8 is small, that is, the sensitivity of the loading factor to nodal installation error was weak for deep K8. The loading capacity of imperfect structures was compared to that of the ideal structures to investigate the change of reduction factor along with stiffness factor. Findings indicate that minimal reduction factor corresponding to a certain joint stiffness decreases with the increase of E_{max}. Different from the influence of initial curvature, the changing range of reduction factor caused by nodal installation error is positively related to structure size. The reduction factor of the deep K8 tended to be the lower limit of the shallow K8, that is, the lower limit of the loading capacity of small-scale dome structures can be considered the lower limit of large-scale domes.

Fig. 16 shows the load–deflection curves of the K8 latticed shell with E_{max}=20 mm, α=0.5, and 1.0. The structural buckling capacity ranged from 0.61 to 0.79 and from 0.65 to 0.87 when joint stiffness was set to 0.5 and 1.0, respectively. In addition, post buckling behavior may be influenced by nodal installation error.

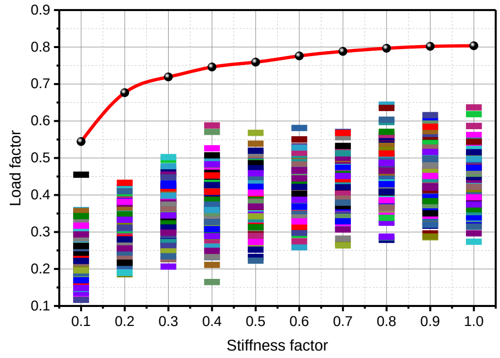


a) E_{max}=15 mm

b) E_{max}=45 mm

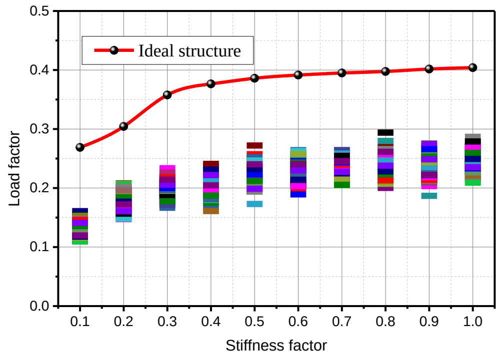


c) E_{max}=133 mm

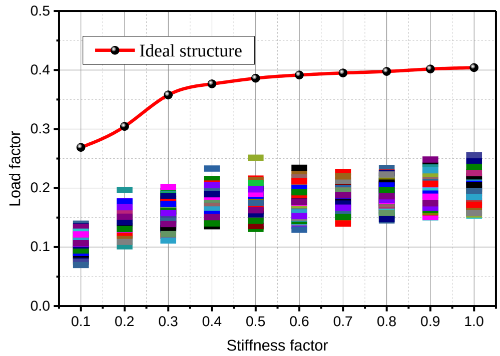


d) E_{max}=400 mm

Fig. 13 Influence of installation error on shallow K8 latticed shell

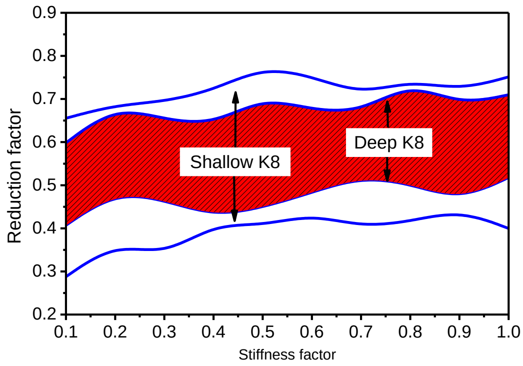


a) E_{max}=133 mm

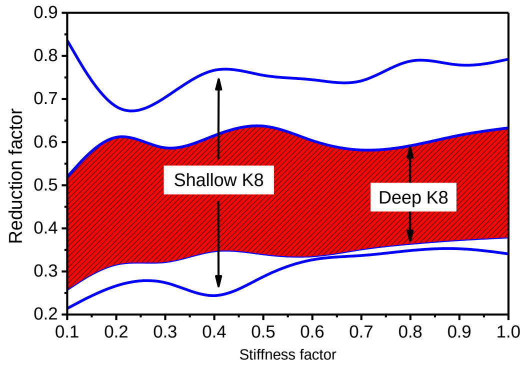


b) E_{max}=400 mm

Fig. 14 Influence of installation error on deep K8 latticed shell

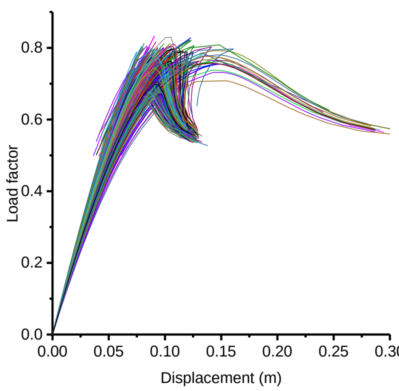


a) E_{max}=133 mm

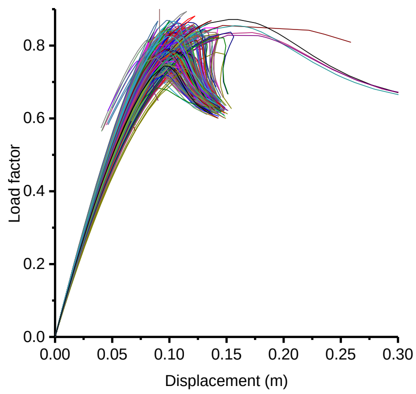


b) E_{max}=400 mm

Fig. 15 Change of reduction factor along with stiffness factor (nodal installation error)



a) E_{max}=20 mm, α=0.5



b) E_{max}=20mm, α=1

Fig. 16 Load-deflection curves of shallow K8 latticed shell

6. Conclusions

A numerical method considering random member initial curvature and nodal installation error was proposed in this study. The randomness of the direction and magnitude of the initial curvature could be considered simultaneously, as well as the joint stiffness. The proposed method could also be adopted for inelastic analysis, and it was proposed based on general finite element software. Hence, tedious programming work could be avoided, and the method could be conveniently utilized by researchers and workers.

Influences of member initial curvature and nodal installation error on the buckling capacity of Schwedler and K8 latticed shells were analyzed. The influence of structure size was further investigated. The influence of the initial curvature direction on the K8 latticed shell could be neglected. The influence of the initial curvature and nodal installation error were related to joint stiffness. Different from the influence of initial curvature, the changing range of reduction factor caused by nodal installation error was positively related to structural size.

Acknowledgments

The work presented in this paper was financially supported by the State Key Research Development Program of China (Grant Nos. 2016YFC0801404 and 2016YFC0600704) and the Project Funded by China Postdoctoral Science Foundation (Grant No. 2017M621156).

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