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Nonlinear stability analysis of a radially retractable hybrid grid shell in the closed position

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Abstract. The buckling capacity of a radially retractable hybrid grid shell in the closed position was investigated in this paper. The geometrically non-linear elastic buckling and elasto-plastic buckling analyses of the hybrid structure were carried out. A parametric study was done to investigate the effects rise-to-span ratio, beam section, area and pre-stress of cables, on the failure load. Also, the influence of the shape and scale of imperfections on the elasto-plastic buckling loads was discussed. The results show that the critical buckling load is reduced by taking account of material non-linearity. Furthermore, increasing the rise-to-span ratio or the cross-section area of steel beams notably improves the stability of the structure. However, the cross section area and pre-stress of cables pose negligible effect on the structural stability. It can also be found that the hybrid structure is highly sensitive to geometric imperfection which will considerably reduce the failure load. The proper shape and scale of the imperfection are also important.

Keywords: retractable roof; grid shell; stability; elasto-plastic; failure load

1. Introduction

Stability plays an important role in the design of the thin shell structure and the grid shell structure, especially the single-layer grid shell structure (Simitses 1976, Schmidt 2000, Bulenda and Knippers 2001). With the increase of the structural span, the stability problem becomes more obvious. A radially retractable hybrid grid shell was proposed by Cai *et al*. (2015). The authors studied the static performance of the hybrid structure, and parametric investigations were carried out to study the effects of key factors (i.e., rise-span ratios, cross-sections of steel beams, cable areas, and the pre-stress of cables) on the static behavior of the structure under symmetric and asymmetric loads. The radially retractable hybrid grid shell, which can be considered as a special form of the grid shell structure, is derived from the single-layer grid shell and tensegrity system. It not only contains a part of properties similar to the grid shell structure, but also possesses its own structural properties. The hybrid grid shell, generally flat with a low rise-span ratio, is always used in the long-span or super-long-span structure. Therefore, the stability problem needs to be studied.

The nonlinear buckling analyses for single-layer reticulated shells based on analytical and non-linear finite element (FE) methods have been developed to trace the equilibrium path by many researchers (Forman and Hutchinson 1970, Gosowski 2003, Gioncu 1995, Liu *et al*. 2015, Meek and Tan 1984, Nie 2003, Sassone and Pugnale 2010, Yang *et al*. 2014, Zhang *et al*. 2013, Zhou *et al*. 2014). The structural behavior of the shell structures during the whole loading process can be described by the load–deflection curves which then give the buckling load. Different buckling modes of grid shells have been investigated by Bulenda and Knippers (2001). They also explained some parameters affecting the failure loads of domes and barrel vaults and gave suggestions for the imperfection shape (Gioncu 1995). However, the material was assumed to be elastic in their study. The analysis of elasto-plastic stability is much more complicated than the elastic analysis since the elasto-plastic analysis involves both geometrical and material nonlinearities. The elasto-plastic stability of the single-layer reticulated shells has attracted more and more attentions from researchers recently (Nee and Halder 1988, Luo 1991, Kato *et al*. 2000, Fan *et al*. 2010, Bai *et al*. 2015). With the fast development of computer technology and the availability of advanced FE software, it is now possible to conduct a comprehensive study on the stability of the hybrid barrel vault through geometrical and material non-linear analyses. Cai *et al*. (2012, 2013a) carried out the elasto-plastic buckling analyses of a perfect hybrid barrel vault/dome and its corresponding single-layer lattice shell. Furthermore, different shapes and sizes of imperfections were considered in this study. Also, the effects of different structural parameters, such as the rise-to-span ratio, beam section dimension, area and pre-stress of cables and boundary

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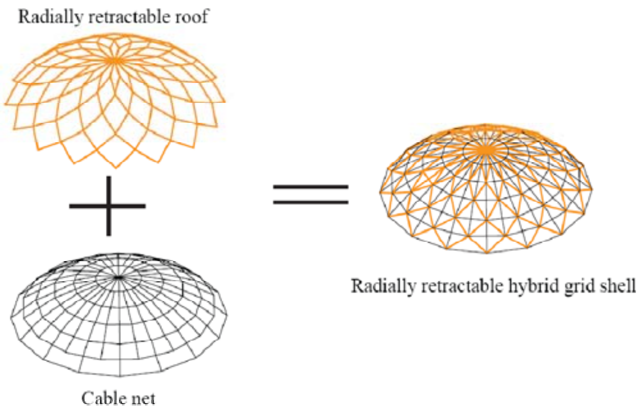


Fig. 1 Radially retractable hybrid grid shell

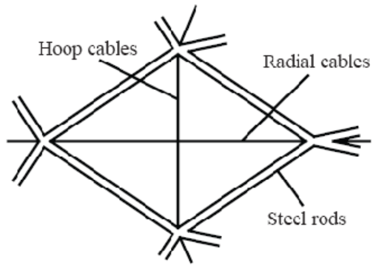


Fig. 2 The arrangement of cables

Fig. 3 The typical joint of the system

conditions, on the failure loads were also investigated. Although the study of the grid shell structure has been carried out by some researches, which leads to a series of prominent achievements, the radially retractable hybrid grid shell is a new-type of structural form, and studies referring to its structural stability have been rarely reported.

This paper shows how to perform a geometrical and material nonlinear finite element analysis by using ANSYS to investigate the stability of the hybrid grid shell in a closed position. Additionally, the effect of factors such as the geometrical and structural parameters and the asymmetrical distribution of loads will also be taken into consideration in this paper. The imperfection sensitivity including the pattern and scale will be investigated.

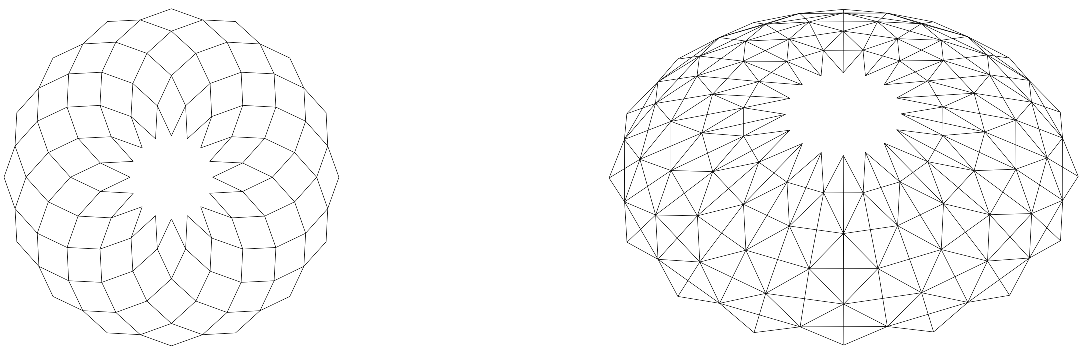
2. Stability behavior of the radially retractable hybrid grid shell

2.1 Retractable hybrid grid shell system

The radially retractable hybrid grid shell was proposed by Cai *et al.* (2015) where the details of this system are given here. The radially retractable hybrid grid shell, as shown in Fig. 1, consists of the radially retractable grid shell and a layer of cable nets. The scissor-like elements are used to form the radially retractable grid shell (Cai *et al.* 2013b, 2014, 2016). The cables are placed at the diagonal lines of the rectangular formed by the scissor-like elements as shown in Fig. 2. The typical joint of the system is shown in Fig. 3. In the deployment progress, the structure unfolds gradually with the driving of support joints of foldable bar structures (as shown in Fig. 4). The radial cables are slack while the length of hoop cables is increasing in this period. Similarly, in the folding progress, hoop cables can be considered as active cables and radial cables passive cables. Then when the structure is totally closed, prestress will be imposed on the hybrid grid shell if active cables are remain stretched. Therefore, it should be that only the single layer grid shell resists external loads in the moving process of the structure. Only when the structure is in the fully closed state, the foldable bar structure and the cable net will work together as the cable supported grid shell structure.

2.2 Finite element model

There are several types of failure due to stability for single-layer reticulated shell: member buckling, local instability, global instability and the combination of above modes. In this study, each strut is simulated by one single beam element without any subdivision in order to avoid



(a) Foldable bar structures (b) Retractable hybrid grid shell

Fig. 4 Deployment state of the system

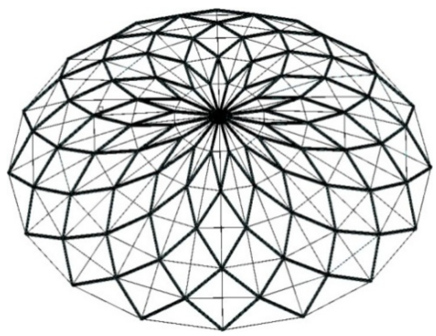
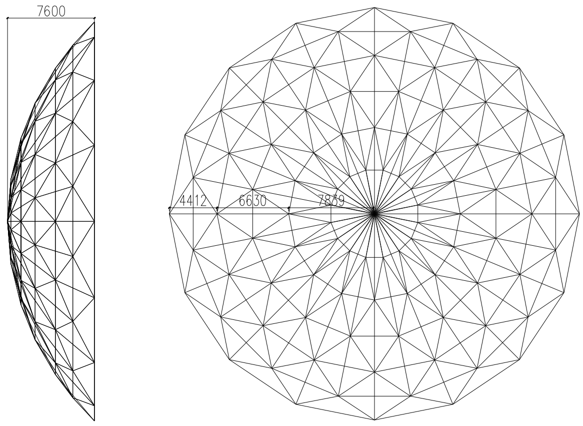


Fig. 5 The studied model



(a) (b)

Fig. 6 Geometry parameters of the hybrid grid shell (mm)

single member buckling achieving less computational time. It should be noted that local member buckling is usually not the decisive mode as was shown in Gioncu (1995). The design example used in this study is shown in Fig. 5. In this model, every multi-angulated rod has six segments, with a projected length of 4 m in the horizontal plane. The inclined angle between adjacent segments is 157.5°. The span of the grid shell is 38 m with the rise/span ratio of 0.2 and other geometric parameters are given in Fig. 6.

The load case 1, a symmetrical load *g*+*s* (dead load + snow load), has been taken into account in all computations. The dead load g consists of a self-weight of 0.5 kN/m^2 including all beams and cables. The snow load is applied on the top surface of the structure in vertical direction with a magnitude of 0.5 kN/m^2 (GB50009-2012 2012). Asymmetrical load case is an important factor that affects the static behavior of hybrid barrel vaults. One type of asymmetrical load is the half-span load which can be resulted from construction or snow. The load case 2, an asymmetrical load case *g*+*s*/2 (*s*/2, the snow load uniformly distributed over half of the span), is considered in this study. The half-span snow load is applied in the left half-span.

In this paper, the finite element software ANSYS is used and the geometric nonlinearity is taken into consideration. As the scissor-like elements are used in this system, the revolute joints are used to connect the steel beams. The technique of coupling degrees of freedom is used. It should be noted that the revolute axis of all scissor joints between angulated rods of dome structures are perpendicular to the plane of projection. Therefore, excluding the rotational degree of *oz* direction, five degrees of freedom of every pair of nodes are coupled in the simulation. The angulated rods are simulated by BEAM188. The boundary of the hybrid grid shell is fixed circularly. Members of multi-angulated rods are made by the box beam with Q345B steel with a cross section of 200 mm × 150 mm × 10 mm (height × width × wall thickness). Elasto-plastic steel material is adopted with a yield stress of 345 MPa. Additionally, the sectional area of the cable, which is simulated by LINK10, is 78.5 mm^2 and the cable is initially prestressed with 100 MPa. The elasticity modulus of steel beams and cables are 210 MPa and 180 MPa, respectively.

2.2 Stability behavior

Fan *et al*. (2010) shows that the influence of the material nonlinearity on the stability of single-layer lattice shell or gird shell structures is significant, and the model containing only geometrical nonlinearity will over estimate the failure load of the structure. As to the radially retractable hybrid grid shell, a new type structural form, the influence of material nonlinearity is still unclear. Therefore, the model only considering geometrical nonlinearity (Model 1) and the model considering both geometrical and material nonlinearity (Model 2) are investigated.

Moreover, the stability behavior of the radially retractable hybrid grid shell and the corresponding single-layer grid shell are studied to investigate the effects of cables. The load displacement curves for the node with the maximum vertical displacement are given in Figs. 7 and 8. The load factor is defined as the ratio between the applied load and the design load. Under the symmetric load case (load 1) and the asymmetric load case (load 2), the failure load of the radially retractable hybrid grid shell considering only geometrical nonlinearity is higher than the system taking account of both geometrical and material nonlinearity, i.e., 38.54% higher in load 1 and 37.62% higher in load 2. Therefore, the model considering geometrical nonlinearity only leads to a relatively risky result and both geometrical and material nonlinearity need to be considered in the analysis of the structure.

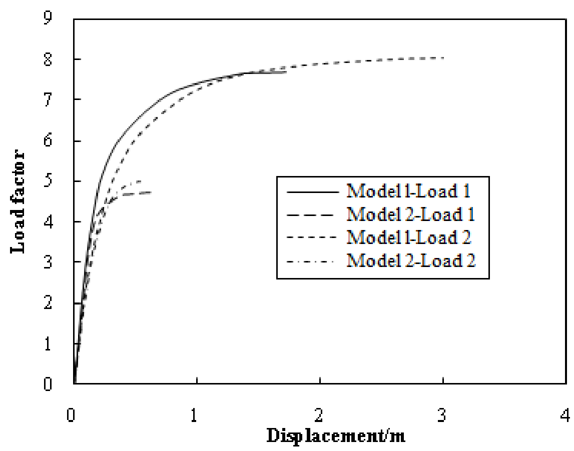


Fig. 7 Load displacement curve of the retractable hybrid grid shell

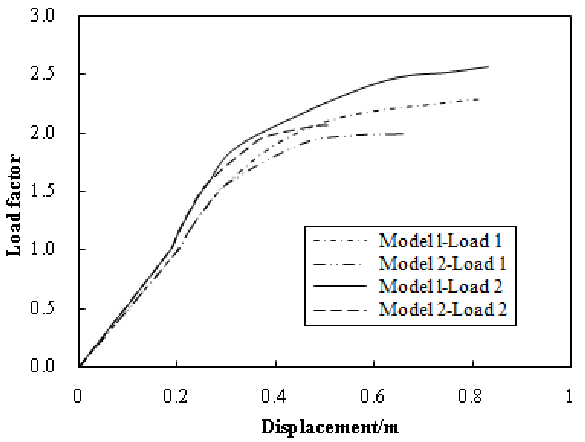


Fig. 8 Load displacement curve of the corresponding single-layer grid shell

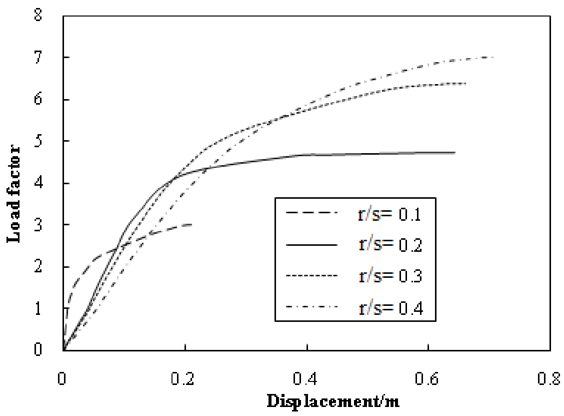
In addition, it can be found that under both load cases, the first half parts of load displacement curves of the two models are very similar. It indicates that the influence of the material nonlinearity at the beginning of the loading process is negligible. With the increase of the loading, the structure shows plastic behavior. Then the slope of the load displacement curve decreases remarkably and the ultimate capacity drops greatly for the elasto-plastic buckling analysis. For the elasto-plastic failure loads of the two modes, the hybrid grid shell increases by 136.63% and 143.19% than the corresponding grid shell.

3. Parametric studies

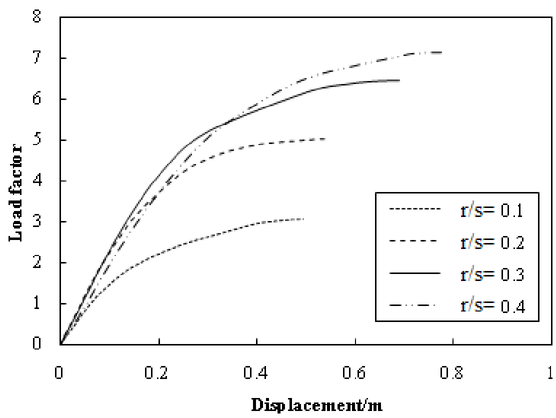
In order to investigate the influence of each structural parameter of the radially retractable hybrid grid shell on the elasto-plastic ultimate capacity of the structure, effects of the rise-span ratios, steel beams sections, initial cable prestress, cable areas are investigated in this paper.

3.1 Influence of rise-span ratios

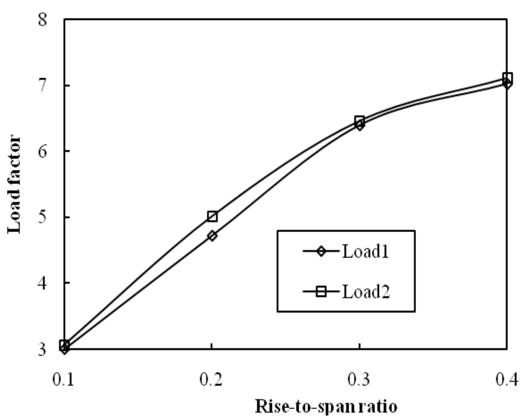
The elasto-plastic analyses are carried out for the example structure but with different rises (keeping the span constant) to study the effect of rise-span ratios. The rise-to-span ratios correspond to 0.1, 0.2, 0.3 and 0.4, respectively. The load displacement curves of the hybrid grid shell with different rise-span ratios and the corresponding failure load factors are shown in Fig. 9. It can be found that the rise-span ratio has a great influence on the stability behavior of the hybrid grid shell and the failure load increases with the increase of the rise-span ratio. For both load cases, the failure load increases significantly when the rise-span ratio is lower than 0.3, but it increases slightly when the rise-span ratio reaches 0.3. It can be concluded that the rise -span ratio is a key factor of the stability capability of the hybrid



(a) Load displacement curves for Load 1

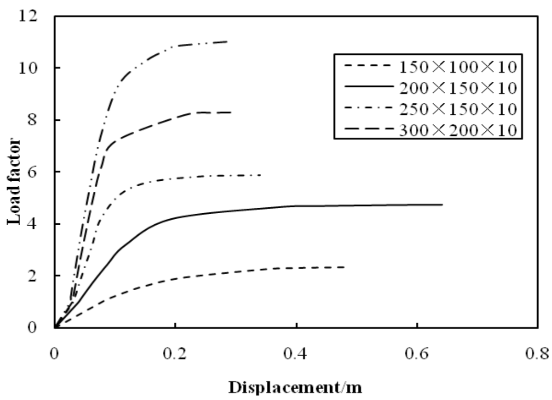


(b) Load displacement curves for Load 2

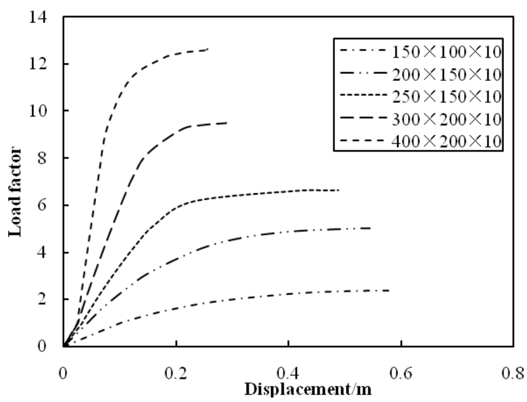


(c) Failure load factor

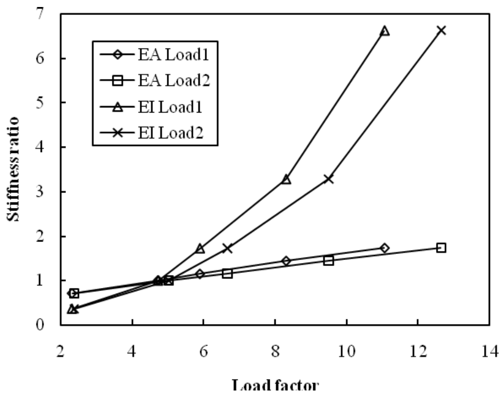
Fig. 9 Influence of rise -span ratio



(a) Load displacement curve under Load 1

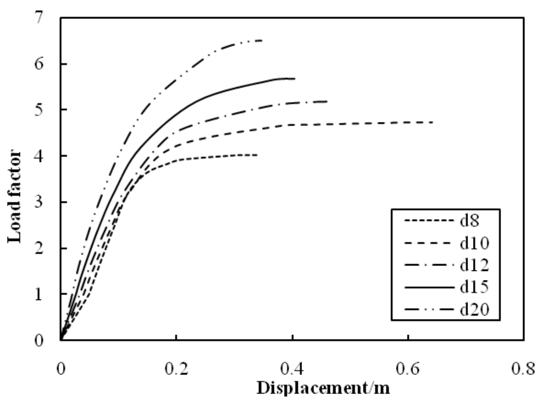


(b) Load displacement curve under Load 2

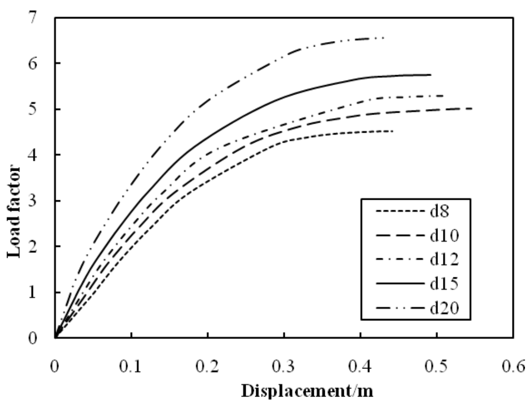


(c) Failure load factor

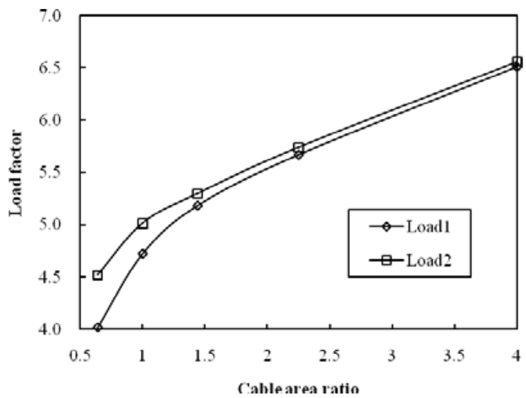
Fig. 10 Influence of the steel beam sections



(a) Load displacement curve under Load 1



(b) Load displacement curve under Load 2



(c) Failure load factor

Fig. 11 Influence of the cable section

grid shell.

3.2 Influence of the steel beam section

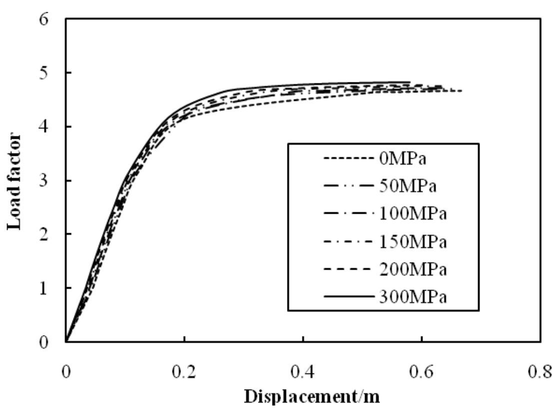
When the geometry of the structure is identified, the cross-section of steel beams can be an important factor that affects the buckling capacity of the hybrid grid shell. This is because the stiffness of the single-layer grid shell mostly relies on the stiffness of beams, which mainly includes the beam axial stiffness EA and flexural stiffness EI. Regarding the beam rigidity of the basic model as E0A0 and E0I0, the stability behavior of the structure is investigated by changing the beam stiffness coefficients EA/ E0A0 and EI/E0I0.

Five different steel beams sections, 150 mm × 100 mm × 10 mm, 200 mm × 150 mm × 10 mm, 250 mm × 150 mm × 10 mm, 300 mm × 200 mm × 10 mm, 400 mm × 200 mm × 10 mm, are chosen to study the influence of beam sections. The load displacement curves are given in Fig. 10. It shows that the tendency of load displacement curves is consistent for different beam sections. It can also be found that the failure load factor of the hybrid grid shell improves with the rise of the bar stiffness. For the symmetric load case, the failure load drops 50.93% when the axial stiffness of bars decreases by 30% and it increases by 24.68% when the flexural stiffness is raised by 70%. For the asymmetric load case, the failure load drops 52.68% when the axial stiffness decreases by 30% and it increases by 32.59% when the flexural stiffness is raised by 70%. It can be obtained from Fig. 10 that the increase of beam sections will enhance the structural stiffness of the hybrid grid shell.

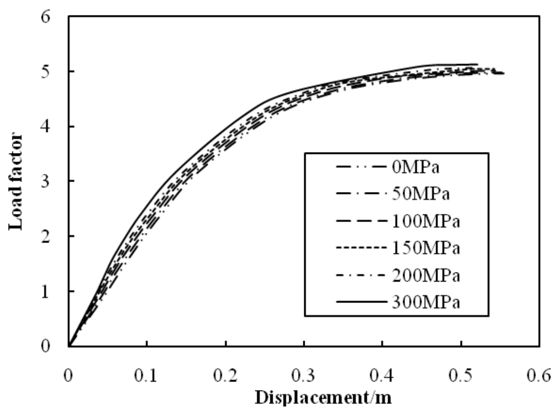
3.3 Influence of the cable area and pre-stress

The pre-stress and area of cables may also be important factors that affect the elasto-plastic buckling behavior of the retractable hybrid grid shell. The load displacement curves and the failure load against the area of cables at the specified cable pre-stress of 100 MPa are shown in Fig. 11. The diameters of cables correspond to 8 mm, 10 mm, 12 mm, 15 mm and 20 mm in Fig. 11, respectively. In Fig. 11(c), the horizontal coordinate represents the cable area coefficient, m, which is defined as the ratio of cable areas to that of the basic model. It can be found from Fig. 11 that, for both load cases, the failure load factor rises with the increase of the cable area. The load displacement curves also show that the effect of the cable area on the structural stiffness is positive. However, it can also be found that the cable area has a limited influence on the ultimate capacity of the hybrid grid shell. Hence, it is not economical to increase the cable area to improve the structure stability behavior.

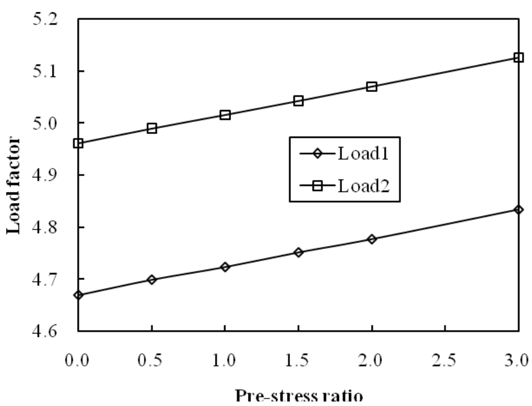
To study the effect of cable pre-stress levels, the initial stresses are set to 0 MPa, 50 MPa, 100 MPa, 150 MPa, 200 MPa and 300 MPa, respectively. The results under both load



(a) Load displacement curve under Load 1



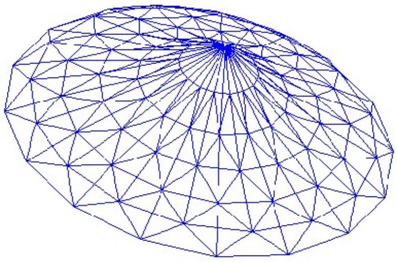
(b) Load displacement curve under Load 2



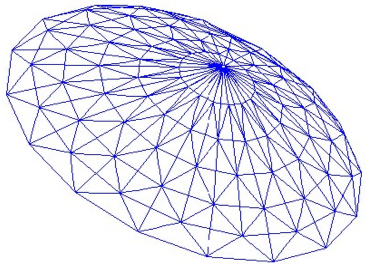
(c) Failure load factor

Fig. 12 Influence of cable prestress

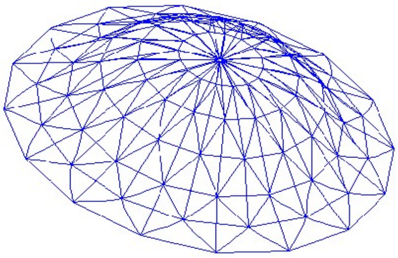
cases are shown in Fig. 12. The cable pre-stress coefficient is defined as the ratio of the cable pre-stress to that of the basic model. It can be seen from Fig. 12 that the ultimate capacity of the hybrid grid shell enhances with the increase of the initial pre-stress level, but the rate of the increase is slight. The ultimate load just increases 1.08% when the prestress level doubles, and it just decreases by 1.08% when the prestress level is reduced to half. It can be concluded



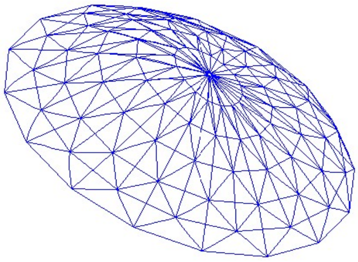
(a) The first eigenvalue buckling mode (Load1)



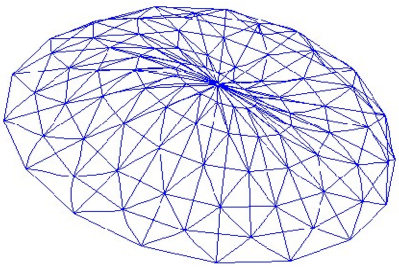
(b) The first eigenvalue buckling mode (Load2)



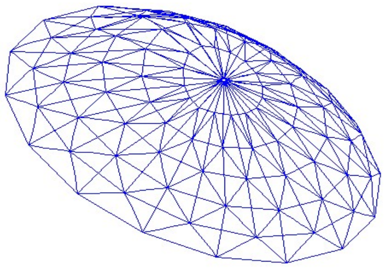
(c) The second eigenvalue buckling mode (Load1)



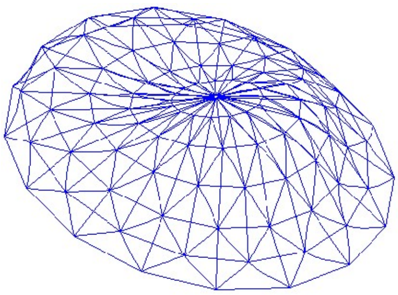
(d) The second eigenvalue buckling mode (Load2)



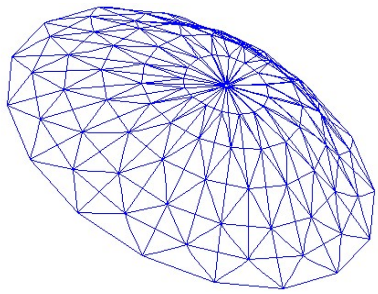
(e) The third eigenvalue buckling mode (Load1)



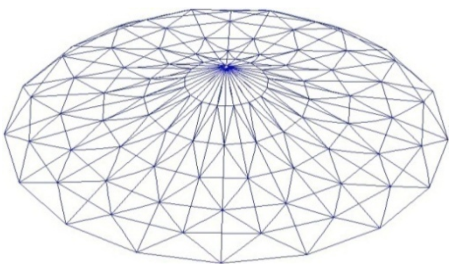
(f) The third eigenvalue buckling mode (Load2)



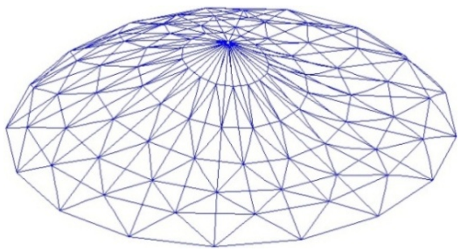
(g) The forth eigenvalue buckling mode (Load1)



(h) The forth eigenvalue buckling mode (Load2)



(i) Nonlinear buckling mode (Load1)



(j) Nonlinear buckling mode (Load2)

Fig. 13 Buckling modes of the radially retractable hybrid grid shell that the cable pre-stress contributes little to the ultimate capacity of the structure. Therefore, it is not an appropriate choice to improve the ultimate capacity of the structure by simply increasing the initial prestress in cables.

4. Effects of imperfections on the stability behavior

The inaccuracy in construction and installation may impose a great influence on the structure (Zhou *et al*. 2016). The single-layer grid shell structure has been found sensitive to imperfections (Cai *et al*. 2012, 2013a). As a new type of single-layer grid shell, the effect of imperfections on the stability of the radially retractable hybrid grid shell has not been studied. According to the European standard (Eurocode 2004) and Chinese code (JGJ7-2010 2010), the geometrical imperfection should be taken into account in the non-linear analysis in order to model the structure in a realistic way.

Several methods are available to analyze geometrical imperfections, e.g., the random imperfection mode method (Yamada 2001), the consistent imperfection mode method etc. The consistent imperfection mode method is used in this paper. Then the shape and the scale of the geometric imperfection are discussed.

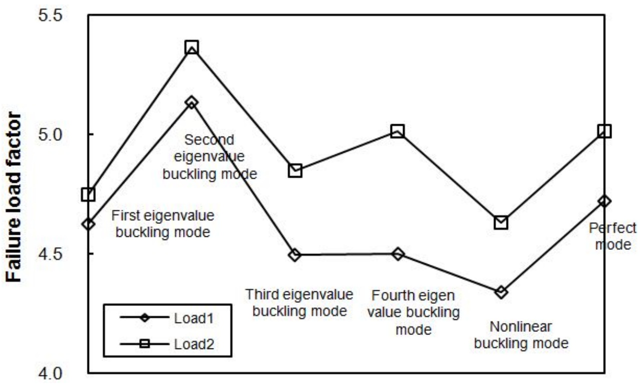


Fig. 14 Influence of imperfection modes on the ultimate capacity of the structure

4.1 Shape of the imperfection

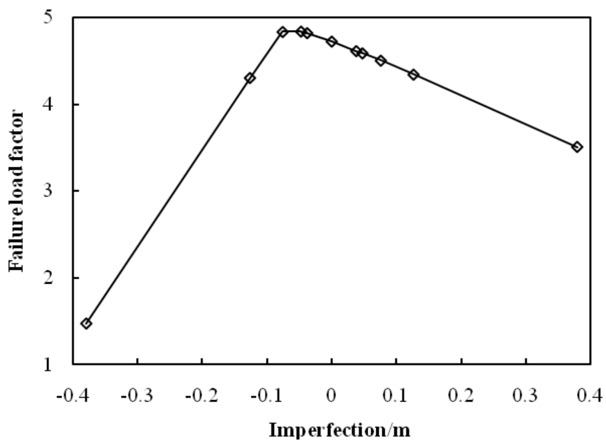
According to the design codes (JGJ7-2010 2010, Eurocode 2004), the first eigenvalue buckling mode is chosen as the imperfection shape. Generally, the buckling capacity that is calculated based on the first eigenvalue buckling mode is lower than those given by higher eigenvalue buckling modes, e.g., single-layer reticulated shells. However, for a pre-stressed space structure, Zhang *et al*. (2006) suggested that the buckling capacity based on other eigenvalue buckling modes may be the lowest. On the other hand, the final buckling shape was proposed by Bulenda and Knippers (2001) to be used as a geometrical imperfection. Therefore, shapes of imperfections for the hybrid grid shell are set up as follows: (1) The first several eigenvalue buckling modes; (2) the displacement shape of the loaded structure obtained from a geometrical non- linear elastic buckling analysis (Cai *et al*. 2012, 2013a).

In this paper, from a preliminary study, the first four eigenvalue buckling modes and the nonlinear buckling mode, which are given in Fig. 13, are chosen.

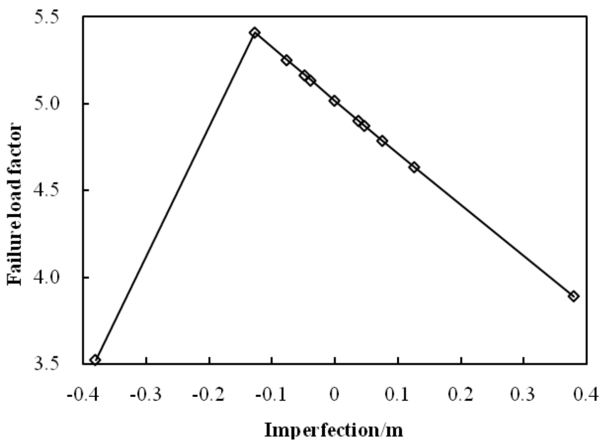
Fig. 14 shows the failure load factors for different hybrid grid shells, including the pristine structure. The maximum imperfections of all shapes have been scaled to span/300. It is clear from the figure that the failure load of the hybrid structure under both load cases is significantly affected by the geometric imperfections. The imperfection based on the second eigenvalue buckling modes is larger than the perfect system. This is because the second eigenvalue buckling modes increases the rise of the system, which leads to the increase of the ultimate capacity. It can be found that the lowest buckling load is predicted with the nonlinear buckling mode. Therefore, this imperfection shape is thus employed in all the following analyses.

4.2 Size of the imperfection

As stated in Cai *et al*. (2012, 2013a), the scaling of the imperfection is as important as its shape. Generally, the span of the structure is taken as a reference scale for the imperfection size (Eurocode 2004). According to the technical specification for space frame structures (JGJ7-2010 2010), the maximum geometric imperfection that is



(a) Load 1



(b) Load 2

Fig. 15 Failure load factors with different sizes of imperfection

Fig. 16 The direction of imperfections

caused by construction should be restricted within span/300. As expected, the buckling capacity of the structure decreases when the maximum nodal displacement due to the geometric imperfection increases. However, for a hybrid structure, the buckling capacity with the maximum imperfection of span/300 may not be the lowest. Therefore, we need to study the influence of the size of the imperfection.

The failure loads corresponding to different sizes of the nonlinear buckling mode are computed. Fig. 15 shows the imperfection sensitivity of the hybrid grid shell structure. In this figure, the negative value of imperfection denotes the imperfections applied in the opposite direction as shown in Fig. 16. It is clear from the figure that the hybrid structure shows high sensitivity to imperfections when the structure is under both the symmetric and asymmetrical loads. The failure load of the hybrid structure decreases when the positive imperfection scale increases (i.e., when the structure is decreasing its nodal deformation due to imperfection). However, the failure load initially increases and then reduces whilst increasing the negative imperfection scale. It is very interesting to note the failure load with negative imperfection scale is higher than that of the perfect structure. This is because the negative imperfections will slightly increase the rise of the hybrid grid shell. Therefore, it is important to know the direction where the imperfection is imposed.

5. Conclusions

The buckling capacity of the radially retractable hybrid grid shell in the closed position was investigated in this paper. The geometrical non-linear elastic buckling analyses was carried our first. By taking into consideration of material non-linearity using elasto-plastic analyses, the behavior of hybrid structures was found significantly different. The results show that the buckling capacity is reduced by taking account of material non-linearity. Then the effects of different geometrical and parameters on the failure loads were studied. The analysis results show that under a particular span, the buckling capacity initially increases with the increase of the rise-to-span ratio. Moreover, increasing the cross-section of steel beams notably improves the stability performance of the structure. However, the area and pre-stress of cables pose virtually little effect on the structural stability. Finally, the effects of imperfections on the stability behavior were also investigated. It can be found that radially retractable hybrid grid shell is highly imperfection sensitive and the reduction of the failure load due to imperfections can be considerable. Furthermore, when imposing imperfections, the proper shape and scale of the imperfection are important. The results show that the nonlinear buckling mode is the most critical imperfection shape. Because the trend of failure load is found not always related to the sign of imperfection scale, great caution should be taken when imposing imperfections along opposite path.

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