RESEARCH ON DISTRIBUTION AND MAGNITUDE OF INITIAL GEOMETRICAL IMPERFECTION AFFECTING STABILITY OF SUSPEN-DOME

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ABSTRACT: Stability calculation is the main content during analysis of suspen-dome. To ensure the analysis results, with consideration initial geometrical imperfection, estimate structural stability reliably, looking for the worst distribution and magnitude of initial geometrical imperfection during stability calculation is the focus in this paper. First, a single-layer latticed shell and three types of suspen-domes are selected to study the influence of initial geometrical imperfection distribution on their overall stability by consistent imperfection mode method. Then, the influence of initial geometrical imperfection magnitude on structural stability was studied by the same method. Using calculation results from above numerical models, different distribution of initial geometrical imperfection, which is adopted during stability calculation, is listed, and the load-displacement curves which can reflect structural overall stability are drawn. Results show that the stability factor is lower when the first antisymmetric buckling mode is adopted as initial geometrical imperfection distribution and its magnitude lays between 1/500 and 1/300 structural span, and structural stiffness is also lower. The conclusions derived from the paper are applicable to similar practical structure.

Keywords: Suspen-dome, Initial geometrical imperfection, Buckling modes, Stability, Aberrance structure, Structural stiffness

1. INTRODUCTION

Stability analysis is the key problem during design of single-layer latticed shell [1]. Even though suspen-dome, which includes the advantage of both tesengrity structure and single-layer latticed shell, is better in stability than single-layer latticed shell [2, 3, 4, 5], stability analysis is also the key problem during design [6, 7, 8]. Until recently, there is little study on stability of suspen-dome, so the theory of single-layer latticed shell in this aspect is always referred in designing practical suspen-dome structure. The upper single-layer latticed shell in suspen-dome is sensitive to geometrical imperfection, so the influence of initial geometrical imperfection, for example erection deviation, must be considered during calculating stability. Initial geometrical imperfection can be considered by several methods, one is the random geometric imperfection mode method, and another is the consistent imperfection mode method which is popular method during design [1, 9]. Zhang etal[10]studied on influence of initial geometrical imperfection distribution on stability of suspen-dome by consistent imperfection mode method, they found that it is unreasonable that the stability of single-layer latticed shell is better than suspen-dome under full-span uniformly distributed service load after considering initial geometrical imperfection. The primary cause might be different initial geometrical imperfection adopted by different structures.

The consistent imperfection mode method proposes that the first buckling mode is adopted as initial geometrical imperfection distribution for single-layer latticed shell, and initial geometrical imperfection magnitude is equal to 1/300 structural span [1, 9]. The proposition is more reasonable for single layer latticed shell whose span is less than 60m. Nonetheless, whether above initial geometrical imperfection is the worst for larger span and more complex structure will be discussed in the paper. Distribution and magnitude of initial geometrical imperfection will be focused latter.

2. ANALYSIS METHOD

With the development of nonlinear finite element method, the structural stability can usually be described by load-displacement curve at present. Because FEM was not available for nonlinear problems in the past, researchers used to utilize continuous theory to transfer single-layer latticed shell into continuous shell, then the stability of shell were calculated by nonlinear analytic method. In 1945, Koiter theory was brought forward, and it played a very important role in development of stability calculation [11].

Principal steps for calculation of structural stability through consistent imperfection mode method are as follows:

(1) Eigenvalue buckling analysis is done first, in order that eigenvalue buckling modes and usually overestimated buckling loads of structure can be obtained from this analysis [12]. The control function for eigenvalue buckling analysis can be stated as follows:

$$([K_e] + \lambda \lfloor K_g \rfloor)\{\psi\} = 0 \quad (1)$$

Where λ is eigenvalue; $\{\psi\}$ is displacement vector; $[K_e]$linear elastic stiffness matrix; $\lfloor K_g \rfloor$ geometric stiffness matrix

(2) The lowest buckling mode is then introduced as initial geometrical imperfections distribution into structure and 1/300 span is adopted as initial geometrical imperfection magnitude.

(3) The nonlinear buckling analysis is conducted to obtain more reliable buckling loads by the load–deflection curves from the nonlinear finite element analysis. Arc-length method and Newton-Raphson (N-R) method are now in widespread use during nonlinear finite element analysis [13].

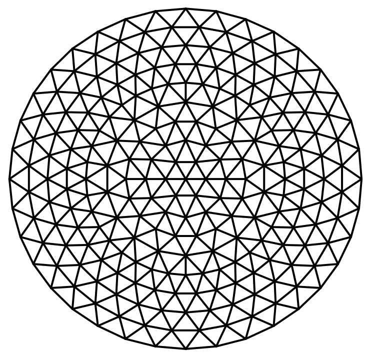
3. INFLUENCE OF INITIAL GEOMETRICAL IMPERFECTION DISTRIBUTION ON STRUCTURAL STABILITY

Single-layer latticed shell, rib3 type suspen-dome, sunflower3 type suspen-dome and rib2-sunflower1 type sunpen-dome are selected to study influence of initial geometrical imperfection distribution on structural stability. During stability calculation, the research objects subject to the full-span uniformly distributed service load, whose value is 1.3kN/m^2.The first several buckling modes are individually adopted as initial geometrical imperfection distribution during analysis in order to study how initial geometrical imperfection distribution influences structural stability. ANSYS program is utilized to calculate structural stability in the paper.

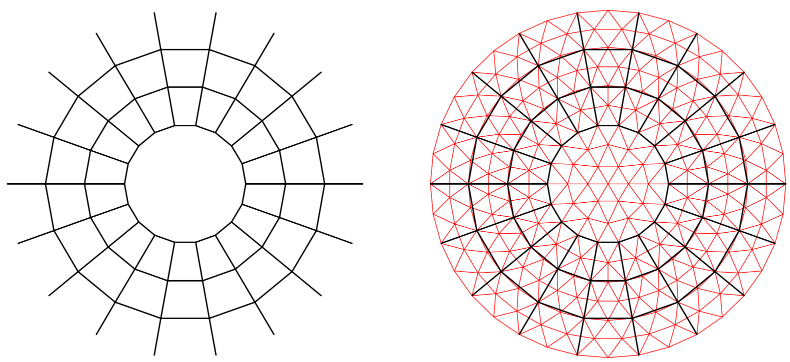
Above four types of structural models are the same in span and rise, their span is 122 meters and rise is 12.2 meters. Concrete arrangement of bottom cable-struts and upper single-layer latticed shell are shown in Figure1. The structural members type, sectional area, modulus of elasticity, and material density are listed in Table1. Prestress force distribution of hoop cable is 1:0.31:0.08, the prestress force of outer hoop cable is 2000kN.

Table 1. Sectional Areas, Material Properties of Components

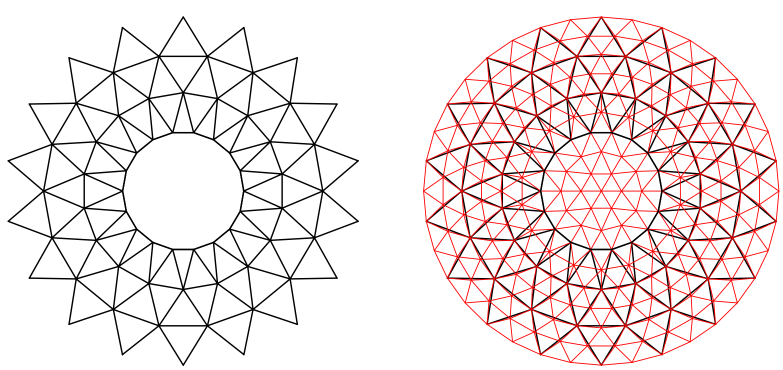
Member	Section (m^2)	Modulus of Elasticity (Gpa)	Density (kg/m^3)	Member	Section (m^2)	Modulus of Elasticity (Gpa)	Density (kg/m^3)
Hs1	0.01124	190	6550	G1	0.00466	206	7850
Hs2	0.00570	190	6550	G2	0.00466	206	7850
Hs3	0.00285	190	6550	G3	0.00466	206	7850
Xs1	0.00562	190	6550	shell	Φ377x12	206	7850
Xs2	0.00285	190	6550	Xs3	0.00285	190	6550



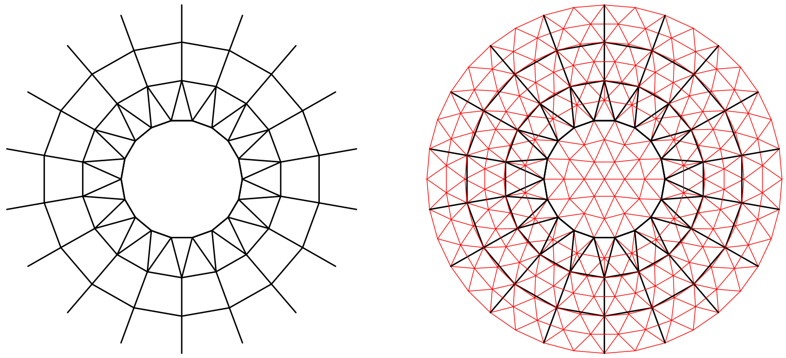
(a) Single-Layer Latticed Shell



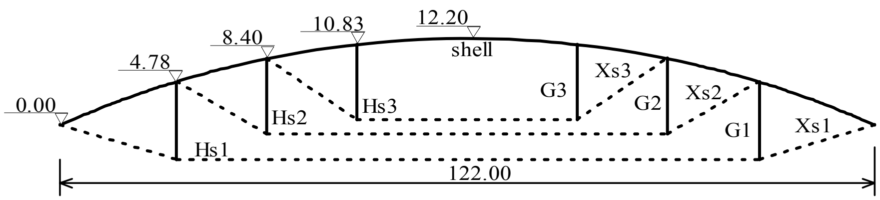
(b) Rib3 Type Suspen-dome



(c) Sunflower3 Type Suspen-dome



(d) Rib2-Sunflower1 Type Suspen-dome



Hs1 is outer hoop cable Xs1 is outer ridial cable G1 is outer strut
Hs2 is middle hoop cable Xs2 is middle ridial cable G2 is middle strut
Hs3 is inner hoop cable Xs3 is inner ridial cable G3 is inner strut

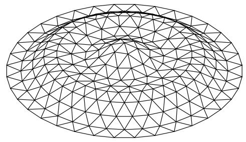
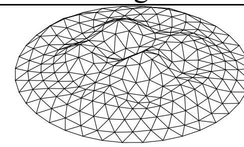
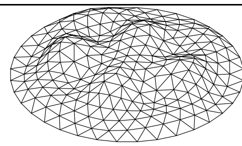
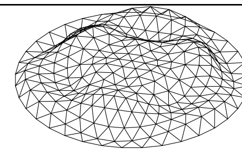
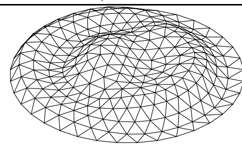
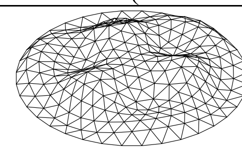
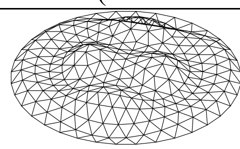
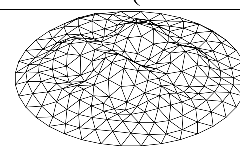
（e）Section Plan of Structure

Figure 1. Calculation Diagram of Model

3.1 Single-layer Latticed Shell

It is well known that single-layer latticed shell is sensitive to geometrical imperfection [1], and single-layer latticed shell is part of suspen-dome [References 2 to 6]. So it is necessary that single-layer latticed shell is firstly selected to study influence of initial geometrical imperfection distribution on its stability. In the stability analysis process, eigenvalue buckling analysis is done first in order that structural buckling modes are obtained and structural ultimate bearing capacity could be expected. Then 13 orders of buckling modes are extracted from results. Some modes are similar in their distribution because of structural symmetry, so 13 orders of buckling modes can be classified into eight groups which are listed in Table 2. After eight types of buckling modes are individually adopted as initial geometrical imperfection distribution, and initial geometrical imperfection magnitude is 1/300 structural span, structure, including initial geometrical imperfection, is calculated by arc length method. In order to know how initial geometrical imperfection distribution influence on structural stability, load-displacement curves are drawn by the nodal displacement which are maximum in displacement results. All curves are shown in Figure 2. The stability results under different initial geometrical imperfection are listed in Table 2 after nonlinear finite element analysis.

Table 2. Eigenvalue Buckling Modes and Stability Factor of Single-Layer Latticed Shell

types	Buckling Mode	types	Buckling Mode
1	 Factor=4.5 (1st order)	5	 Factor=2.9（8th、9th order)
2	 Factor=2.4 (2nd、3rd order)	6	 Factor=2.6 (10th order)
3	 Factor=2.1 (4th、5th order)	7	 Factor=2.5 (11st order)
4	 Factor=3.1 (6th、7th order)	8	 Factor=3.0 (12nd、13rd order)

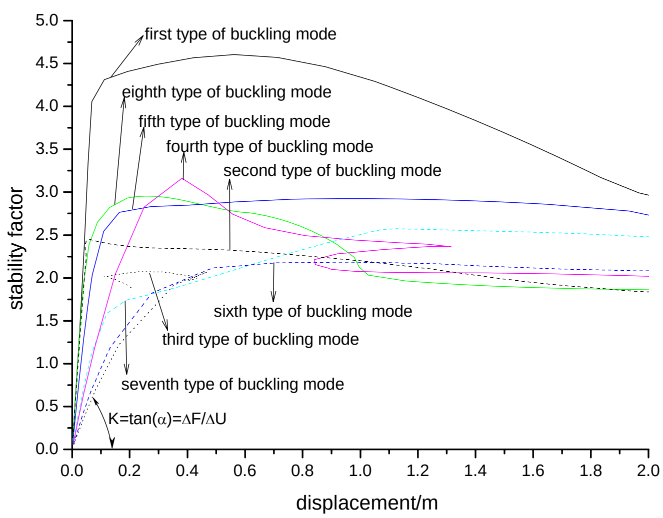


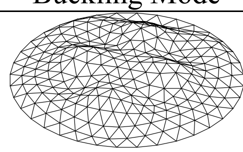
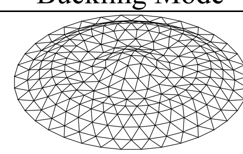
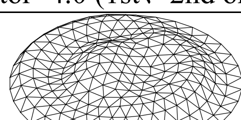
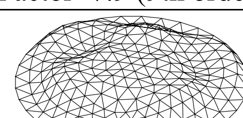
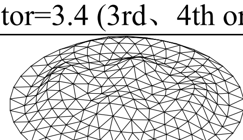
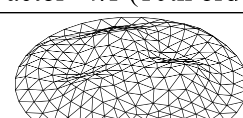
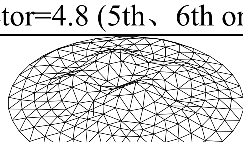
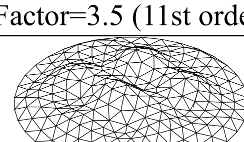
Figure 2. Load-Displacement of Single-Layer Latticed Shell

Figure2 shows that influence of initial geometrical imperfection distribution on structural stability is evident, and there are obvious differences in load-displacement curve under different initial geometrical imperfection. When the first type buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is equal to 4.5, which is maximal in all numbers. Here we can draw a line tangent to load-displacement curve, and define the structural stiffness by the tangent change (K as shown in Figure 2). From Figure 2 we can also see that the structural stiffness is the best in all cases when the first type buckling mode is adopted as initial geometrical imperfection distribution. While the third type buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is equal to 2.1, which is minimal in all numbers, and the structural stiffness is the worst in all cases. The results show that when the first type buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is not minimal for single-layer latticed shell. From Table 2 we can see that the first type buckling mode is symmetry and its middle part is bulge. The third type buckling mode, however, is antisymmetric, and its order is minimal in all antisymmetric buckling modes. When the stability factor is not minimal after adopting the first buckling mode as initial geometrical imperfection distribution, the results from usual consistent imperfection mode method will not reliably assess structural stability. The above-mentioned facts need further study, similar research on suspen-domes will be done later.

3.2 Rib3 Type Suspen-Dome

Rib3 type suspen-dome is selected to study influence of initial geometrical imperfection distribution on structural stability by similar process. Eigenvalue buckling analysis is done first, 13 orders of buckling modes are extracted from results; secondly, 13 orders of buckling modes are classified into eight groups which are listed in Table 3. After eight types of buckling modes are adopted as initial geometrical imperfection distribution individually, and initial geometrical imperfection magnitude is 1/300 structural span, structure, which includes initial geometrical imperfection, is calculated by N-R method. The stability factors are shown in Table 3 and load-displacement curves are shown in Figure 3.

Table 3. Eigenvalue Buckling Modes and Stability Factor of Rib3 Type Suspen-dome

Types	Buckling Mode	Types	Buckling Mode
1	 Factor=4.0 (1st、2nd order)	5	 Factor=7.9 (9th order)
2	 Factor=3.4 (3rd、4th order)	6	 Factor=4.1 (10th order)
3	 Factor=4.8 (5th、6th order)	7	 Factor=3.5 (11st order)
4	 Factor=4.1 (7th、8th order)	8	 Factor=4.6(12nd、13rd order)

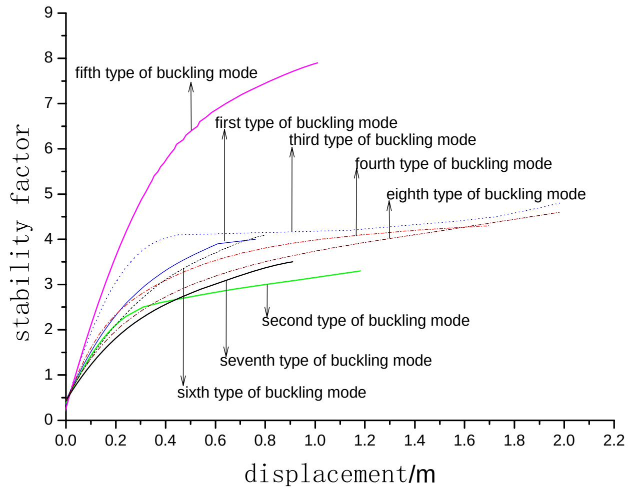


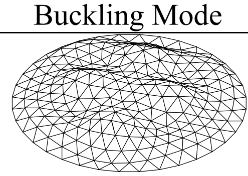
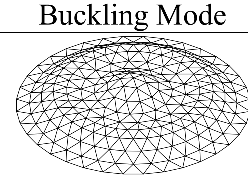
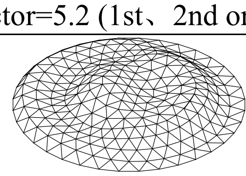
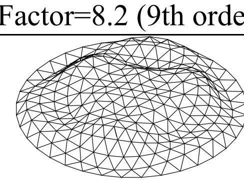
Figure 3. Load-Displacement of Rib3 Type Suspen-dome

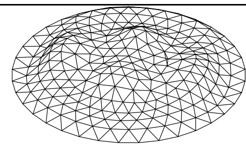
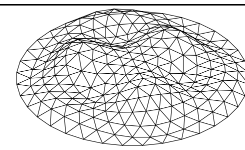
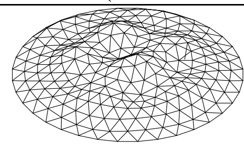
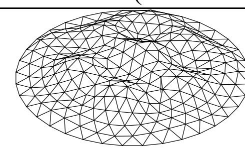
The computational results show that when the second type buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is equal to 3.4, which is minimal in all numbers, and the structural stiffness is worse. The stability factor is not minimal after adopting the first buckling mode as initial geometrical imperfection distribution. While the stability factor is maximal after adopting the fifth type buckling mode as initial geometrical imperfection distribution and the structural stiffness is the best in all cases. From Table 3 we can see that the fifth type buckling mode is symmetrical and its middle part is bulge, the second type buckling mode, however, is antisymmetry, and its order is minimal in all antisymmetry buckling modes. From above two structures we can see that the mode corresponding to minimal stability factor is antisymmetry, while the mode corresponding to maximal stability factor is symmetry.

3.3 Rib2-Sunflower1 Type Suspen-Dome

Rib2-sunflower1 type suspen-dome is also selected to study influence of initial geometrical imperfection distribution on structural stability by similar process. The results are listed in Table4 and shown in Figure4.

Table 4. Eigenvalue Buckling Modes and Stability Factor of Rib2-Sunflower1 Suspen-dome

Types	Buckling Mode	Types	Buckling Mode
1	 Factor=5.2 (1st、2nd order)	5	 Factor=8.2 (9th order)
2	 Factor=3.0 (3rd、4th order)	6	 Factor=4.8 (10th order)

3	 Factor=5.3. (5th、6th order)	7	 Factor=3.7 (11st order)
4	 Factor=4.2 (7th、8 th order)	8	 Factor=4.6 (12nd、13rd order)

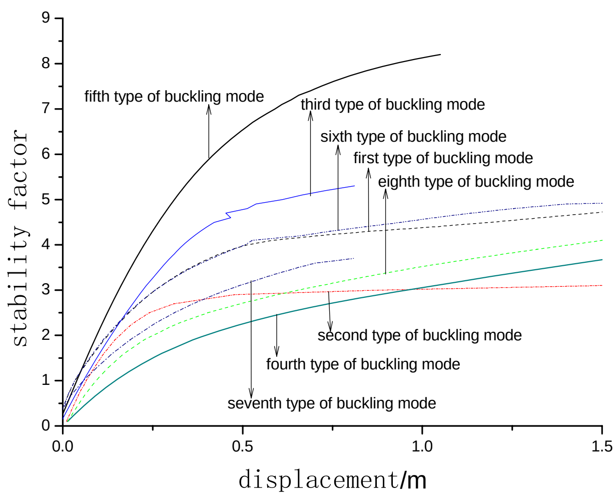


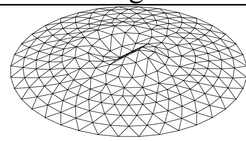
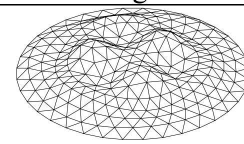
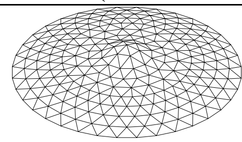
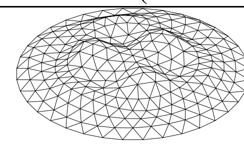
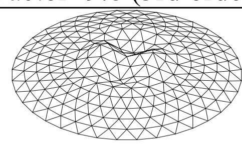
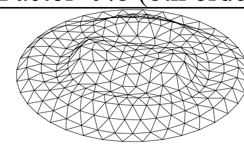
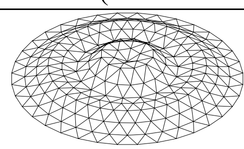
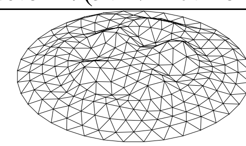
Figure 4. Load-Displacement of Rib2-Sunflower1 Type Suspen-dome

The computational results show that when the second type buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is equal to 3.0, which is minimal in all numbers, and the structural stiffness is the worst in all cases. While the stability factor is maximal adopting the fifth type buckling mode as initial geometrical imperfection distribution and the structural stiffness is the best in all cases. From Table4 we can see that the fifth type buckling mode is symmetrical and its middle part is bulge, the second type buckling mode, however, is antisymmetry, and its order is minimal in all antisymmetry buckling modes. From above three structures we can see that initial geometrical imperfection distribution corresponding to the first buckling mode might be not the worst distribution.

3.4 Sunflower3 Type Suspen-Dome

In order to know which initial geometrical imperfection distribution is the worst for stability, sunflower3 type suspen-dome is also selected to study. The results are listed in Table 5 and shown in Figure 5.

Table 5. Eigenvalue Buckling Modes and Stability Factor of Sunflower3 Type Suspen-dome

types	Buckling Mode	types	Buckling Mode
1	 Factor=4.1 (1st、2nd order)	5	 Factor=7.4 (7th order)
2	 Factor=9.8 (3rd order)	6	 Factor=9.8 (8th order)
3	 Factor=6.6 (4th、5th order)	7	 Factor=7(9th、10th order)
4	 Factor=8.6 (6th order)	8	 Factor=8.7 (11st、12nd order)

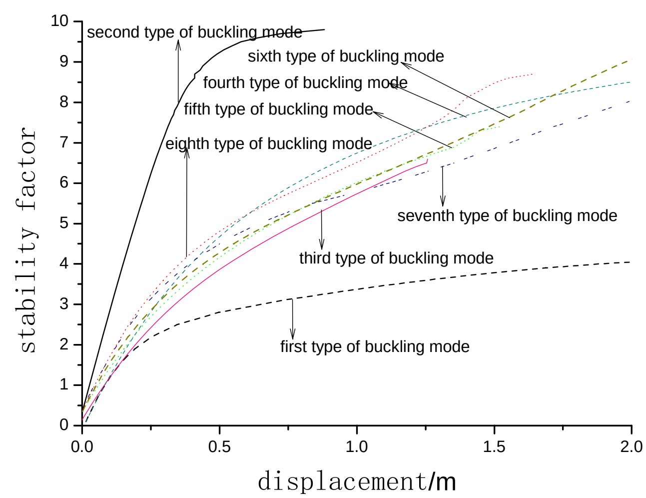


Figure 5. Load-Displacement of Sunflower3 Type Suspen-dome

The computational results show that when the first buckling mode is adopted as initial geometrical imperfection distribution, the stability factor is equal to 4.1, which is minimal in all numbers, and the structural stiffness is the worst in all cases. It is identical with literature [1, 9]. But the stability factor is 9.8 adopting the second type buckling mode as initial geometrical imperfection distribution and the structural stiffness is the best in all cases, the result is beyond our imagination. From Table.5 we can see that the second type buckling mode is symmetrical and its middle part is bulge, the first order buckling mode, however, is antisymmetry, and its order is minimal in all antisymmetry buckling modes.

Finally, synthesizing the above research results, we can see that influence of initial geometrical imperfection distribution on structural stability is evident, and structure owns different stability under different initial geometrical imperfection, and initial geometrical imperfection distribution corresponding to the first buckling mode might not be the worst distribution. At the same time, from above computational results we can see that the stability factor which adopted the first antisymmetry buckling modes is lower than first buckling modes and the structural stiffness is worse. As a result, the first antisymmetry buckling mode is adopted as initial geometrical imperfection distribution in structural stability analysis is proposed. When initial geometrical imperfection distribution is symmetry and its middle part is bulge, the stability factor is maximal, which is even more than perfection structure, so this type of distribution can not be adopted as initial geometrical imperfection distribution during structural stability analysis in case potential safety problem exits list in the structure.

4. INFLUENCE OF INITIAL GEOMETRICAL IMPERFECTION MAGNITUDE ON STRUCTURAL STABILITY

Factors affecting initial geometrical imperfection are its distribution and its magnitude. In the process of above research on influence of initial geometrical imperfection distribution on structural stability, initial geometrical imperfection magnitude is not allowed to vary in order to remove its influence on structural stability, and its value is always equal to 1/300 structural span. So the research on influence of Initial geometrical imperfection magnitude on structural stability will give fuller understanding to influence of Initial geometrical imperfection on structural stability.

Literature [9] pointed out that distance and height deviation between any control supporting points in single-layer latticed shell must be checked when structure is inspected, distance deviation must be less than 1/2000 distance between two supporting points, and be less than 30mm; height deviation must lay between -20mm and +20mm when structural span is less than 60m; when structural span is more than 60m, height deviation must lay between -30 and +30. The above initial geometrical imperfection magnitude adopted in stability calculation has been out of standard which proposed in Literature [9]. Vertical deviation is more severely restricted than horizontal deviation when structure is inspected, but vertical deviation is much bigger than horizontal deviation in above buckling modes. Shen and Chen [1] pointed out that the structure might become an aberrance structure after adopting initial geometrical imperfection whose magnitude is too large, when structure becomes an aberrance structure, its stability might be much better than corresponding perfection structure. An aberrance structure, however, has worse structural stiffness，so it will has much more deformation than normal structure under the same loads, its better stability is meaningless in practical structure. From Figure5 we can see that the stability factor of sunflower3 suspen-dome including sixth type buckling mode is much better, but its deformation is too large, so we can say that structure has become an aberrance structure after adopting sixth type buckling mode as its initial geometrical imperfection. In order to select proper initial geometrical imperfection magnitude during structural stability analysis, above four types of structures are selected again to study influence of initial geometrical imperfection magnitude on structural stability. During latter study, initial geometrical imperfection distribution is not allowed to vary in order to remove its influence on structural stability, and it is corresponding to the first antisymmetry buckling mode. and initial geometrical imperfection magnitude are 0、1/2000、1/1400、1/1200、1/1000、1/800、1/600、1/500、1/400、1/300、1/200 structural span individually. The results under different initial geometrical imperfection magnitude are shown in Figure6-Figure9, the rules of stability to initial geometrical imperfection magnitude are shown in Figure10.

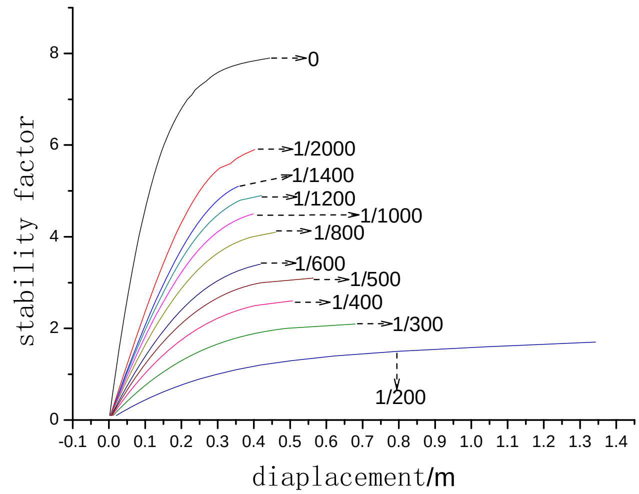


Figure 6. Load-Displacement Curves of Single-Layer Latticed Shell under Different Initial Geometrical Imperfection Magnitude

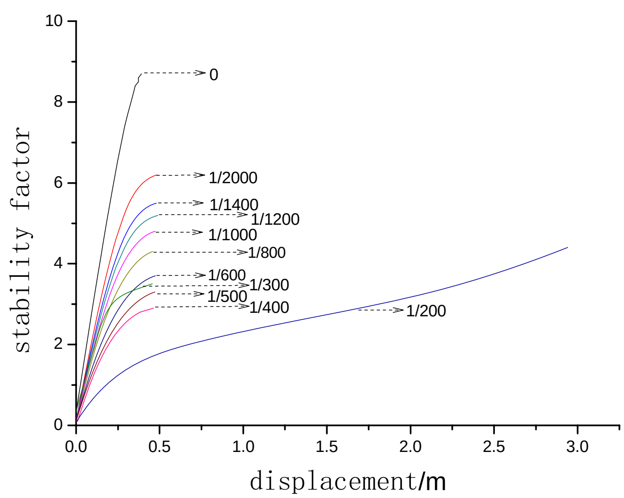


Figure 7. Load-Displacement of Rib3 Type Suspen-dome under Different Initial Geometrical Imperfection Magnitude

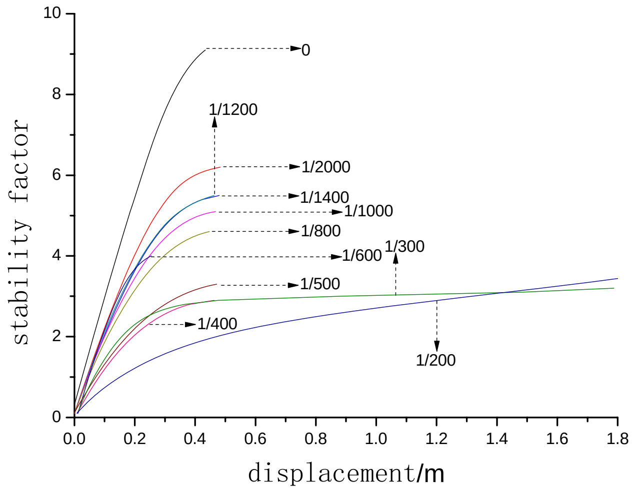


Figure 8. Load-Displacement Curves of Rib2-Sunflower1 Type Suspen-dome under Different Initial Geometrical Imperfection Magnitude

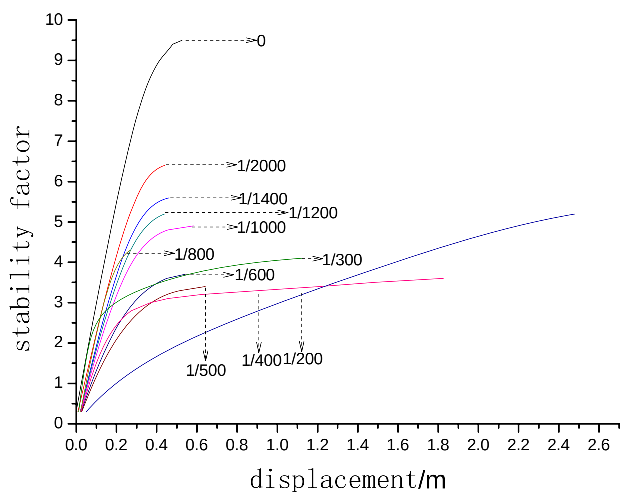


Figure 9. Load-Displacement of Sunflower3 Type Suspen-dome under Different Initial Geometrical Imperfection Magnitude

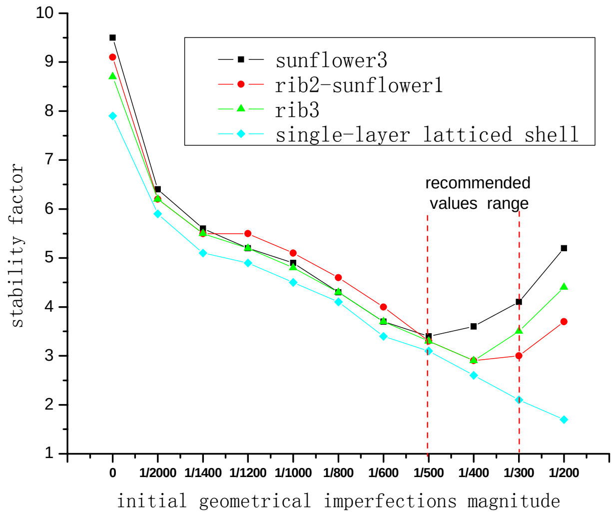


Figure 10. Variation of Stability Factor under
Different Initial Geometrical Imperfection Magnitude

The computational results show that the stability factor including initial geometrical imperfection, whose magnitude is 1/2000 structural span, is evidently less than perfection structure, it can be said that structural stability is sensitive to initial geometrical imperfection. As initial geometrical imperfection magnitude increases, structural stiffness is significantly reduced. Structural stability usually descends as initial geometrical imperfection magnitude increases, but structural stability of rib3 type, rib2-sunflower1 type and sunflower3 type suspen-dome are enhanced when initial geometrical imperfection magnitude is 1/200 structural span. From Figure6-9, we can see that structural stiffness is reduced evidently when initial geometrical imperfection magnitude is 1/200 structural span, and is the worst in all cases. So we can say that structure has become an aberrance structure when initial geometrical imperfection magnitude is 1/200 structural span. Although its stability factor is enhanced to a certain degree, its stiffness is reduced evidently. From Figure10 we can see that as initial geometrical imperfection magnitude increases, structural stability factor significantly declines steadily at the initial stages, structural stability factor, however, begins to enhance after initial geometrical imperfection magnitude reach certain value. It proves that it is wrong that the more initial geometrical imperfection magnitude, the worse structural stability capacity would be.

Overall，structural stability is sensitive to initial geometrical imperfection. And the greater initial geometrical imperfection magnitude the worse structural stiffness would be. Structural stability significantly declines at the initial stage, however begins to enhance after initial geometrical imperfection magnitude reaches a certain value, which might make structure become an aberrance structure. From the above results, we can say that above structures all have become aberrance structures when initial geometrical imperfection magnitude reaches 1/200 structural span. As initial geometrical imperfection magnitude increases, the point, at which structural stability begins to change, is different for different structures. For instance, rib3 and rib2-sunflower1 type suspen-dome would start changing when initial geometrical imperfection magnitude is 1/400 structural span, sunflower3 type suspen-dome would start changing when initial geometrical imperfection magnitude is 1/500 structural span. A designer should be concerned about the value of this point because structural stability and stiffness at this point are worst. Overall the point always lays between 1/500 and 1/300 structural span. So a designer should stay on the safe side and obtain initial geometrical imperfection magnitude between 1/500 and 1/300 structural span by test computations. Initial geometrical imperfection must be proper during stability calculation to prevent structural design being unsafe or uneconomical.

5. CONCLUSIONS AND SUGGESTIONS

Based on the study, the results could be employed to give some advice for how to set distribution and magnitude of initial geometrical imperfection during design for suspen-dome and similar large span structure. Conclusions and suggestions are made as follows:

(1) Suspen-dome stability is sensitive to initial geometrical imperfection.

(2) Stability factor adopting the first antisymmetry buckling modes is lower than first buckling modes and the structural stiffness is worse.

(3) It is proposed that the first antisymmetry buckling mode could be adopted as initial geometrical imperfection distribution during structural stability analysis.

(4) As initial geometrical imperfection magnitude increases, structural stability capacity significantly declines steadily at the initial stage, however, begins to enhance after initial geometrical imperfection magnitude reach a certain value, which might make structure an aberrance structure.

(5) A designer should stay on the safe side and obtain initial geometrical imperfection magnitude between 1/500 and 1/300 structural span by test computations.

(6) Initial geometrical imperfection magnitude and distribution must be proper during stability calculation. If the corresponding structural design is not safe or economical, further investigation is needed.

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