STRUCTURAL DESIGN OF A PRACTICAL LARGE-SPAN CABLE-FRAME TYPE OF SUSPENDED SINGLE-LAYER RETICULATED SHELL WITH FREE SURFACE

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ABSTRACT: Cable-frame type of suspended single-layer reticulated shells with free surface proposed by the author of the present paper is a novel type of large-span hybrid spatial structures. The whole design procedure regarding a practical gymnasium steel roof using this structural system is presented. System constitution including form finding of the upper structure and shape determination analysis of the lower cable-bar system is given out in details and emphasized. Load/action effects are thoroughly summarized for member sections design. A special joint design when diagonal cables penetrating the corresponding upper steel beam member is also brought forward. Hopefully the present paper could benefit the further research and practical engineering on hybrid spatial structures.

Keywords: Suspended single-layer reticulated shell, Shape determination analysis, Spatial cable frame, Hybrid spatial structures, Joint design

1.   INTRODUCTION

Space structures hybridizing a stiff system and a flexible cable-bar system (a single-layer reticulated shell with free surface plus a cable-bar tension system) are designated as hybrid spatial structures. Cable-stayed or suspension lattice shells, planar/spatial beam/truss-string structures, and spherical suspend-domes are all hybrid spatial structures and have been built world widely. Theoretical study and reports on practical engineering experiences disperse numerously in journal papers. This is not convenient for scholars or structural engineers to learn of or solve a certain problem.

Past Work on Spherical Suspen-domes

Kawaguchi et al. [1, 2] proposes a spherical hybrid spatial structures designated as "Suspen-dome" more than 15 years ago. Finite element method (FEM) analysis and structural model test on a suspen-dome with a diameter of 3m and a rise of 0.45m concluded that the axial force within the lattice member of suspen-dome is about 1/3 of corresponding members of the single-layer reticulated shell when working independently. Static non-linear geometrical stability of the suspen-dome is about 1.5 times of that of the single-layer lattice shell. An ideal 200m-span suspen-dome is analyzed and suggests a possible application of suspen-dome to very large-span roofs [2].   Tatemichi et al. [3] conducts a vibration test on a full-size suspen-dome. Kang et al. [4] presented their work on some problems of the structural design of suspen-domes. Zhang et al. [5-6] proposes a universal strategy-local analysis method for force finding analysis of hybrid space structures such as beam-string structures, suspen-domes, and other kinds of hybrid space structures. A rib-ring type of suspen-dome with lower cable-bar system of Geiger type was studied. Construction feasibility due to compatibility requirement of the upper single-layer reticulated shell is put forward. Zhang [7] emphasizes on the optimal pre-stress distribution by using genetic algorithm. Chen et al. [8] propose a rigid suspen-dome for the roof of the VIP hall of Tianjin museum. An experiment was performed under static load. Zhang et al. [9] gives out the whole structural design procedure in details with respect to the largest spherical suspen-dome built in the world at present. A new force finding

analysis strategy designated as linear deduction method is presented. This suspen-dome is also the first one adopting rib-ring type of lower cable-bar system. Zhang [10] developed a universal computational algorithm for shape determination problem of general hybrid spatial structures.
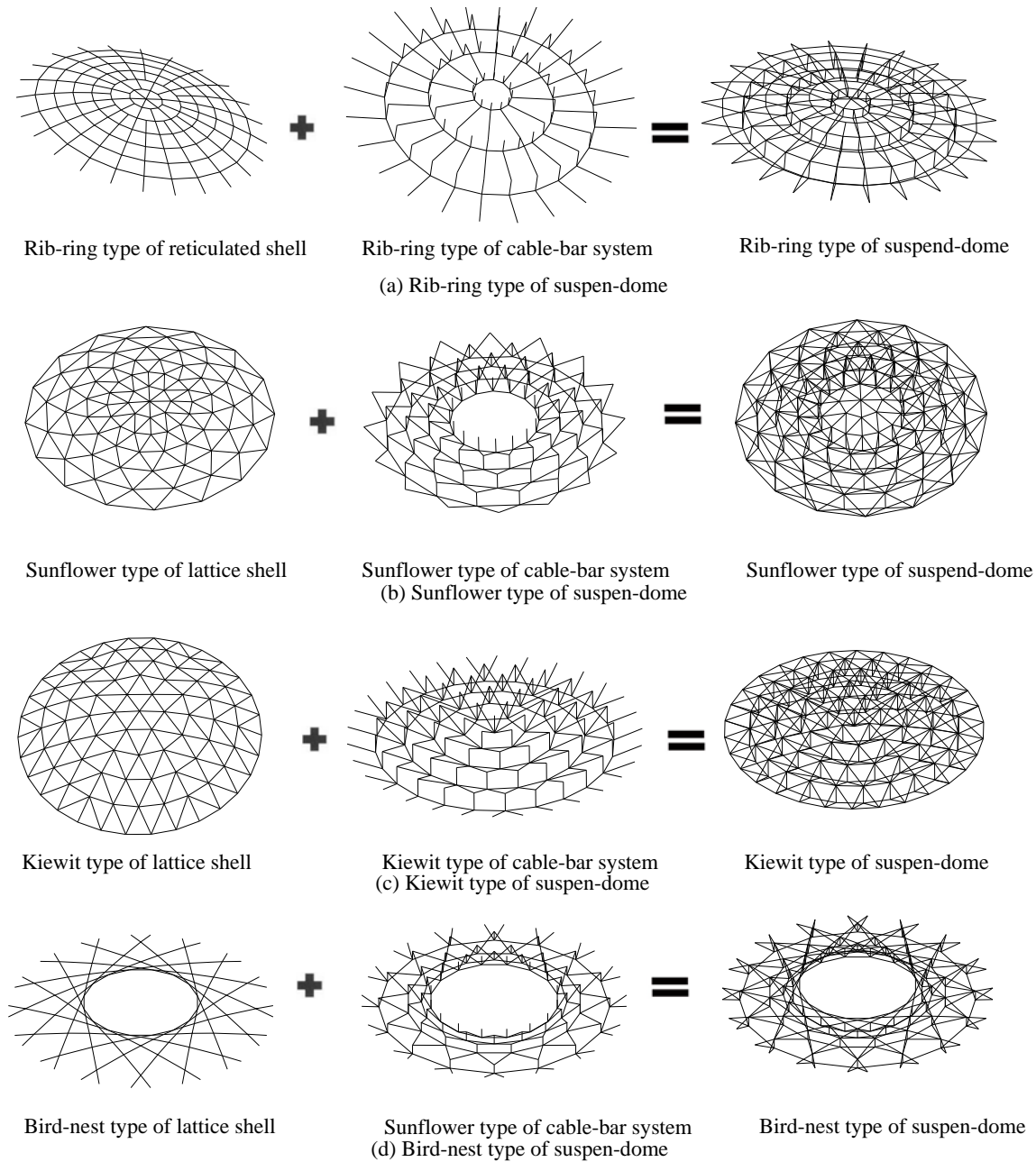
Rib-ring type of reticulated shell   Rib-ring type of cable-bar system   Rib-ring type of suspend-dome

(a) Rib-ring type of suspen-dome

Sunflower type of lattice shell   Sunflower type of cable-bar system   Sunflower type of suspend-dome

(b) Sunflower type of suspen-dome

Kiewit type of lattice shell   Kiewit type of cable-bar system   Kiewit type of suspen-dome

(c) Kiewit type of suspen-dome

Bird-nest type of lattice shell   Sunflower type of cable-bar system   Bird-nest type of suspen-dome

(d) Bird-nest type of suspen-dome

Figure 1. Basic Types of Spherical Suspen-dome

Basic Types of Spherical Suspen-domes

Spherical suspend-domes can be classified by several characteristics of their upper structures and lower cable-bar system.

(1) According to different forms of lower cable-bar system rib-ring type (Figure 1a), sunflower type (Figure 1b), and Kiewit type (Figure 1c) of spherical suspend-domes are given out in Figure 1.

(2) On the basis of the lattice forms of the upper single-layer reticulated shell, they can be called as rib-ring type, sunflower type, Kiewit type, and bird-nest type of suspen-dome.

It should be pointed out that the lattice form of the upper single-layer reticulated shell could commix Kiewit type and sunflower type or others. The same to the lower cable-bar distribution.

Characteristics of Spherical Suspen-domes

[1] Maximum axial internal forces within the upper structure of suspen-dome reduce to 1/3 or so of that of an individual single-layer reticulated shell under same downward dead load. The upper and lower structures work together. Thus the ultimate load-carrying capacity ability of the whole system is higher too.

[2] Not only the lower cable-bar system but also the upper stiff structure need shape determination analysis. This is usually ignored in practical engineering.

[3] Suspen-dome can constitute a self-equilibrated system dependent on the abutment styles.

Representative Suspen-domes Built in China

Figure 2 gives out the system constitution of the Peking Olympic game tennis arena, built in 2006, with a span of 93m in Peking Industry University. This spherical suspend-dome contains 5 loops of sunflower type of lower cable-bar system. Figure 3 is lotus arena in Jinan city, built in 2008, with a diameter of 122m. A Sunflower-Kiewit hybrid lattices is adopted for the upper spherical single-layer reticulated shell. This spherical suspend-dome composes of 3 loops of rib-ring type of lower cable-bar system. Figure 4 is Yubei gymnasium in Chongqing city, Sichuan province in China. Pyramidal shape is distinctive. Figure 5 shows Nansha gymnasium in Guangzhou city in China, built in 2009, with a diameter of 98m. The author of the present paper does not know that there exists this gymnasium until finishing designing Yueqing Olympic center and preparing this paper. Someone might deem it a spatial beam-string structure. Single beam-string structure substitutes stiff beam members for the upper chord cable of single planar cable-frame. This roof system is actually a cable-frame type of suspended rib-ring type of single-layer reticulated shell. The difference between spatial beam-string structures and cable-frame type of suspended single-layer reticulated shells lies in the circular member of the upper lattice shell. Ideal spatial beam-string structures these circular members are for purpose of out of plane instability. Thus they should be pin-jointed with radial members. Anyway this is not important with respect to denominating an attractive structural system.
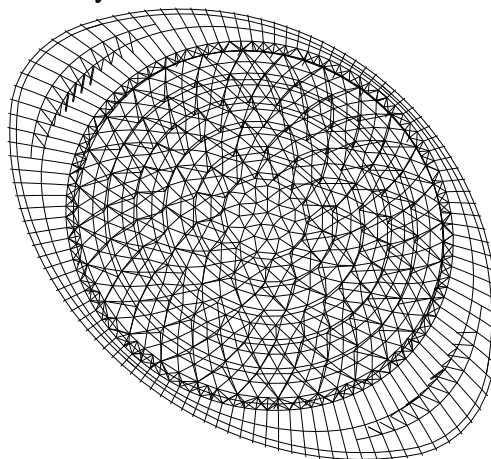

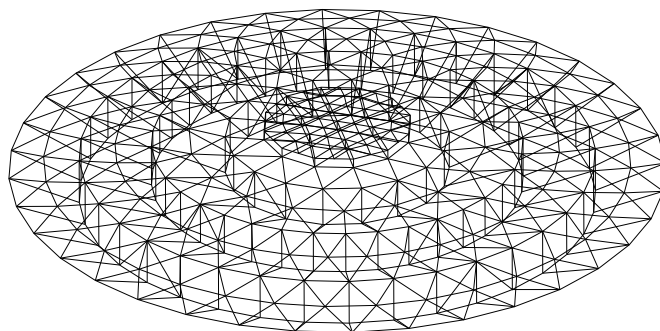Figure 2. Peking Industry University Tennis Arena
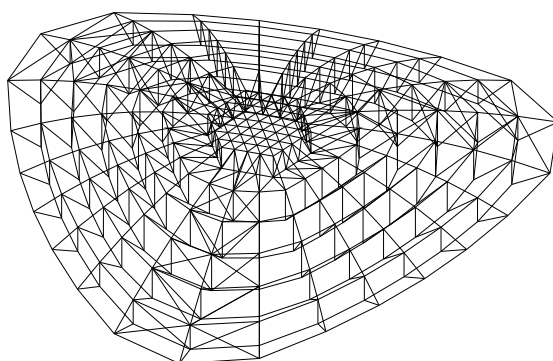
Figure 3. Jinan Olympic Center Lotus Arena

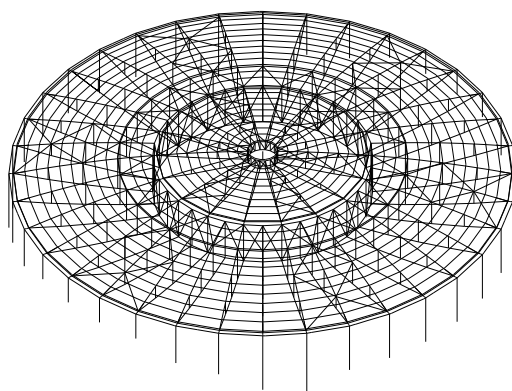Figure 4. Chongqing Yubei Gymnasium

Figure 5. Guangzhou Nansha Gymnasium

Development of Suspended System

Upper single-layer reticulated shells with free surface plus lower cable-dome [11-12] type or cable-frame [13] type of cable-bar system is herein designated as suspended single-layer reticulated shells with free surface (Figure 6). This appellation comprises suspen-dome with spherical single-layer reticulated shells, suspended cylindrical single-layer reticulated shells, spatial beam/truss-string structures, and other suspended systems.

Basic types of suspended single-layer reticulated shells

(1) According to the character of the upper single-layer reticulated shell with free surface, it can be classified as suspended single-layer reticulated shells with regular (there exists algebra equation) or irregular free surface.

(2) On the basis of the cable-bar system distribution, there are cable-dome type and cable-frame type of suspended single-layer reticulated shells with free surface.

Characteristics of suspended single-layer reticulated shells

(1) System constitution is simple. Indoor and outdoor architectural effects are good.
(2) The upper structure member internal forces distribute evenly and the whole system is more stable than an individual single-layer reticulated shell with free surface.
(3) Shape determination analysis of the lower cable-bar system is indispensable and of most importance. If possible form-finding analysis of the upper reticulated shell could be carried out by structural engineers. Hoop cable in common sense will be not in a horizontal plane and paunch bars will be not vertical any more.
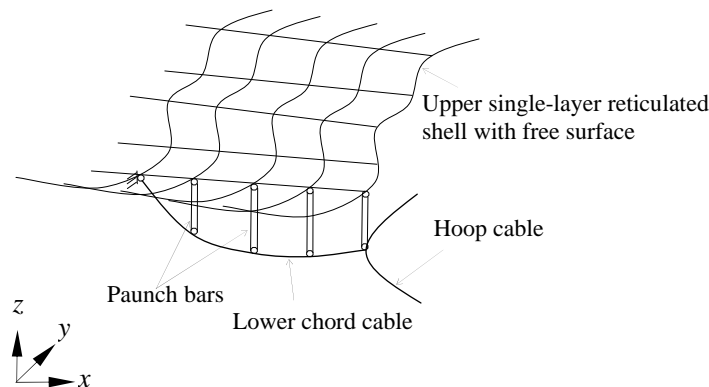

Figure 6. Suspended Single-layer Reticulated Shell with Free Surface

Cable-frame type of suspended single-layer reticulated shell with free surface in practice

The author of the present paper just finished designing Yueqing Olympic center composed of a stadium and two arenas (main gymnasium and swimming arena adopt the same structural system, but the span of the gymnasium is larger than that of the swimming arena). The gymnasium (Figure 7-8) composes of a rigid supporting system (inclined V-shaped columns and upper and lower ring-beams), an upper rib-ring type of single-layer reticulated shell with minimal surface, and a cable-frame type of lower cable-bar system which penetrates the upper corresponding radial beams. Plan view of the whole roof system is an ellipse with long axis span 148m and short axis span 128m. The top level of the upper horizontal ring-beam is 28m. Metal roof covering materials are adopted. There is a circular center at top of the inner roof with a diameter of 40m at a level of 25m. This inner circular plane is divided into 8 and 24 grids. The minimal surface shell is divided into 24 grids as rib-ring shaped. The lower chord cable, paunch bars and paunch cables, and spatial hoop cables constitute a stable lower cable-bar system. Figure 7 gives out the constitution of the whole system. Figure 7a is the stiff grid structures. Figure 7b is the flexible tension system. By combining Figure 7a and Figure 7b a novel cable-frame type of suspended single-layer reticulated shell is shown in Figure 7c. Figure 8 provides the south, west and sectional elevation of the whole system. From Figure 8 it is noted that the hoop cable is not in a horizontal plane and is also not circular. This is rational due to a non-evenly distributed spatial flexibility in vertical direction of the upper reticulated shell and supporting system. Figure 8c shows that the lower chord cable penetrates the corresponding upper radial beam, thus it is a continuous cable. Paunch bars and paunch cables provide proper supporting or hauling action on the reticulated shell. Lower chord cable is more efficient. It is noted that paunch members are not vertical. Inside and under this steel roof system there is the reinforced concrete structure which is well separated except necessary link-beams when designing foundations.

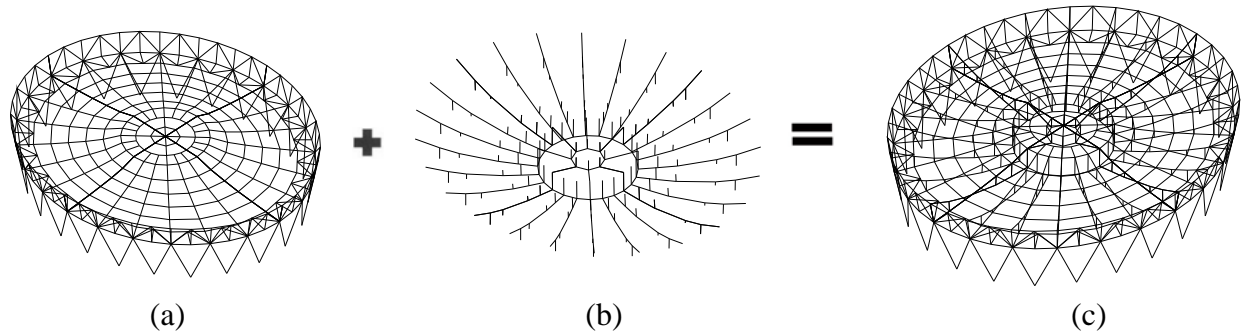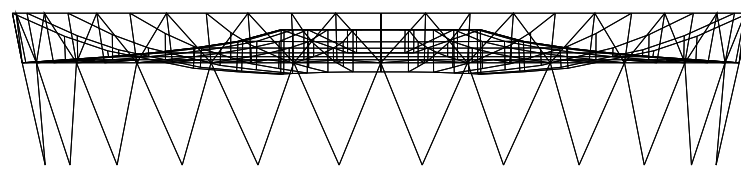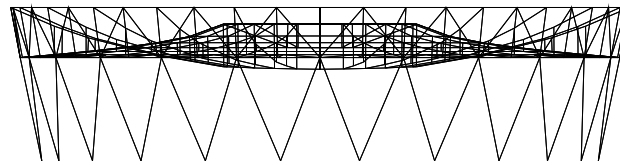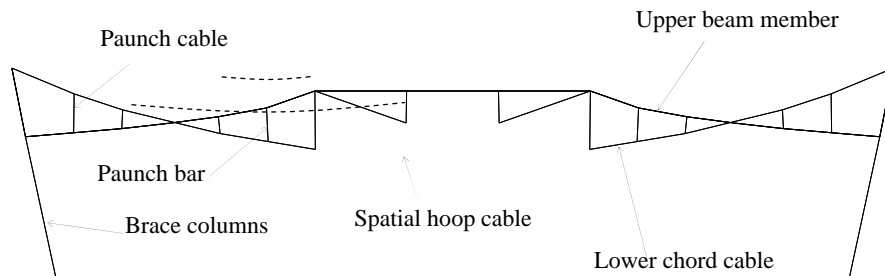(a)   (b)   (c)

Figure 7. Yueqing Olympic Center Gymnasium

(a) West Direction Elevation

(b) South Direction Elevation

(c) South Sectional Elevation

Figure 8. South and West Elevations

The design procedure put forward in the present paper is basically the same for a 2-phase design of tensioned structures. a) Shape determination analysis, and b) Load/action effects analysis. Emphasis is herein addressed on the shape determination analysis of this steel roof system. Form finding analysis of the upper single-layer reticulated shell is conducted using force density method and scattered data interpolation techniques. Shape finding of the lower cable bar system is based on the computational algorithm given out in the reference [10]. Hence in Section 2 it focuses on the details and results of computation process. In section 3, load/action effects such as gravity load due to self-weight of structural members and appended mechanical and electric facilities, wind load, environmental temperature variation, and seismic load for etc. are shortly summarized. In Section 4 some details of special joints of this roof system is put forward.

2.   SHAPE DETERMINATION ANALYSIS-CONSTITUTING SYSTEM

Shape determination analysis is the first step of structural design. How to constitute the whole system according to architectural design concept or requirements is emphasized in this section.

2.1   Fundamental Theory

Some computational tools including dynamic relaxation method, force density method, scattered data interpolation, and local analysis method for the structural design of cable-frame type of suspended single-layer reticulated shells are briefly introduced in this section.

Dynamic relaxation method

Dynamic relaxation method [15-16] has been popularly used in many numerical analysis fields such as linear elastic analysis of thin shells and vaults, load analysis of spatial or planar frames and form finding or load analysis of tensile structures. The pseudo mass or pseudo damping is used to change a static problem into a dynamic one, so it is also called as pseudo transient analysis method. The most important advantage of DRM is that it is a lucid and stable automatic algorithm and needs less memory of computer. It works well to get the accurate solution of the problems which FEM cannot solve easily, such as form finding analysis of tensile structures and load analysis of zero initial stiffness system.

Force density method

Force density method was put forward by H. J. Schek in 1974 in application to form finding analysis of cable-nets [17]. Assuming a certain force density value (usually it refers to ratio of axial tension to the length of the corresponding member), on the basis of the nodal equilibrium conditions a linear algebra equation group about the nodal coordinates can be obtained. Solve this linear algebra equation group to get the final spatial shape of cable-nets or other membrane structures. The present paper utilizes force density method for shape finding analysis of the minimal surface of the upper single-layer reticulated shell. For pure form finding analysis problems force density method is lucid and fast. But it is found that the final shape is closely related with the value of force density and the grid topology.

Scattered data interpolation

After form finding analysis using force density method of the upper single-layer reticulated shell, it is necessary to carry out scattered data interpolation for a proper roof grid. It is because of the final grid shape and size given out by force density method might not be suitable for practical engineering and distribution of the lower cable-bar system. Theory of scattered data interpolation can be found in the references [18-19]. The present paper develops a short program using Matlab.

Local analysis method

General hybrid spatial structures are composed of two parts: the upper structure and the lower structure (Figure 7a and Figure 7b). Sequence of Local analysis method [6] in application to pure force finding analysis of hybrid spatial structures is from the lower part (Figure 7b) to the upper part (Figure 7a). The geometrical configuration of the lower cable-bar system is artificially determinate in advance. The equivalent upward axial forces of the lower system at the upper node of vertical bars is equal to the reaction force of the upper structure (Figure 9) at added supports under self-weight load and others. Local analysis method is also available for shape determination

problem of hybrid spatial structures. But computational sequence is from the upper part to the lower part since the geometrical configuration is unknown beforehand.

The equivalent upward support in vertical bars of lower system (Figure 10) is equal to the reaction force from the upper structure (Figure 9) under additional gravity loads and self-weight of beam members. This can be understood as appending vertical zero-displacement constraints to the upper structure (Figure 9). By linear elastic analysis of the upper structure as shown in Figure 9, vertical reaction forces can be obtained. If additional gravity loads and the self-weight of beam members of the upper structure ideally distribute in a certain way, vertical bars of the lower system will be still vertical and their design pre-compression $t_{vBi}(i=1,2,\cdots,n)$ will be equal to the reaction forces (Figure 10).   Further explanation of shape determination problem of hybrid spatial structures is presented in the reference [10].
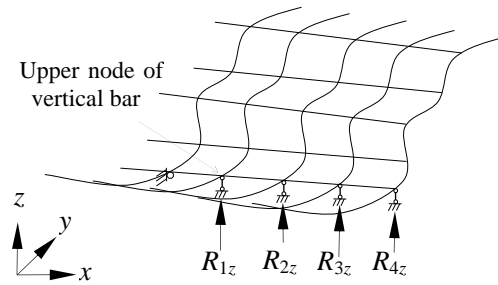

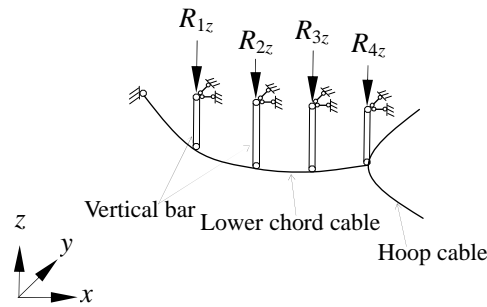Figure 9. The Upper Structure (Single-layer Reticulated Shell with Free Surface)


Figure 10. The Lower Structure

2.2   Form Finding of the Upper Single-layer Reticulated Shell

The supporting system including the upper and lower steel ringbeams and V shaped inclined columns is decided by the architect. And it is also known at first that there is a circular inner plane with a diameter of 40m at a level of 25m. According to this information a rough model is built as shown in Figure 11a and Figure 11b.
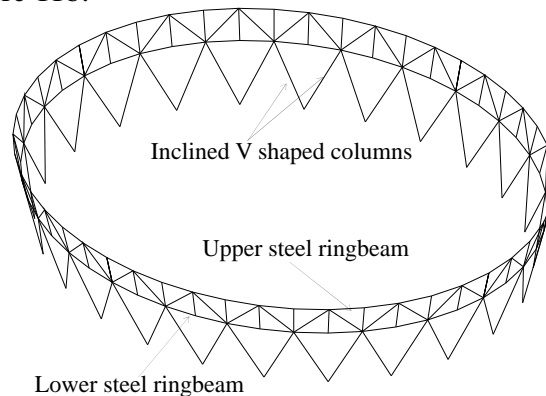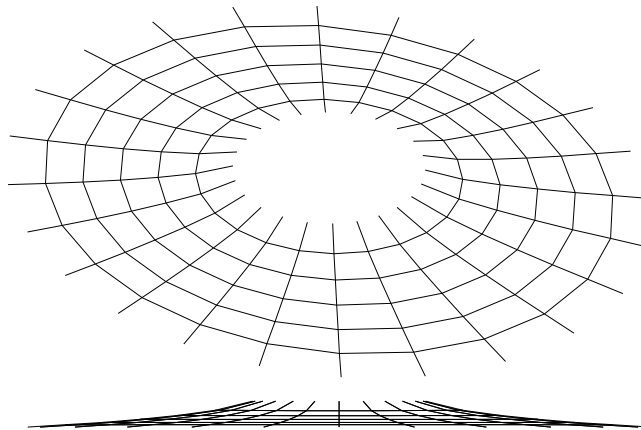

(a) Supporting System Decided by Architects
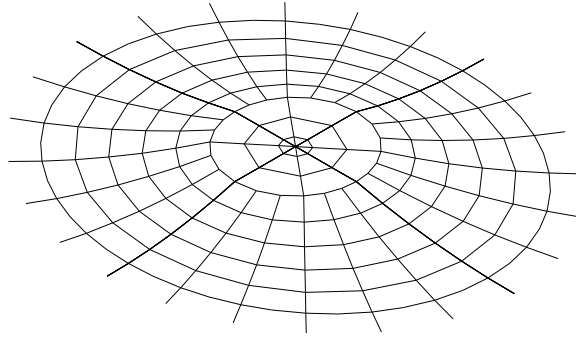
(b) Rough Grid of the Upper Reticulated Shell
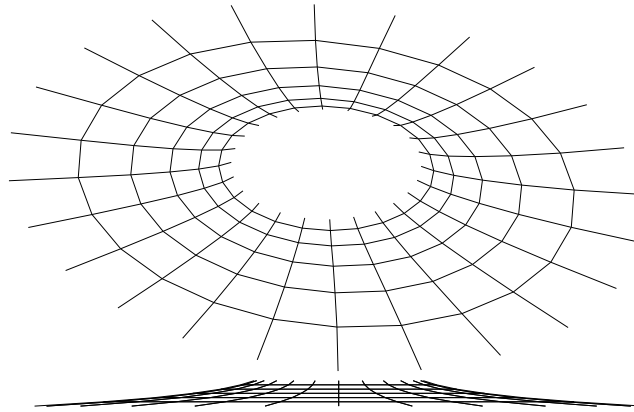
(c) Minimal Surface of the Upper Reticulated Shell after
Form Finding using Force Density Method

(d) Minimal Surface after Interpolation

Figure 11. Form Finding Analysis and Scattered Data Interpolation

Shape geometry in Figure 11a is known at first from architectural design. The upper and lower steel ringbeams are horizontal deposited. The upper steel ringbeam is designed with an outer diameter of 1700mm with C40 concrete inside. The central inner circle at a level of 25m is also decided by architects. Thus only the lattice shape between the inner circle and the lower ringbeam is left for structural engineer. Figure 11b gives out a rough grid shape for form finding analysis by using force density method. Figure 11c shows the final shape after form finding. It is noted that the

cicular members is at intervals of 1m. Figure 11d is from Figure 11b and Figure 11c by scattered data interpolation. *x* and *y* direction nodal coordinates in Figure 11d is the same with that in Figure 11b. *z* direction coordinate is interpolated on the minimal surface of Figure 11c. A short program is developed by Matlab as follows.

Interpolation.m

load originalxy.txt

ox=originalxy(:,3);

oy=originalxy(:,4);

load newxyz.txt

nx=newxyz(:,3);

ny=newxyz(:,4);

nz=newxyz(:,5);

Z=griddata(nx,ny,nz,ox,oy);

plot3(ox,oy,Z,'o'), hold on

After these steps above, there is another step to decide the section size of the stiff system including the supporting system and upper single-layer reticulated shell. This can be conducted by using commercial structural design & analysis software such as Sap 2000 or Midas Gen. A rough geometry of lower cable-bar system is shown in Figure 12a. In case of section size determination of stiff system cables and bars are attached and are assumed to be two-node beam elements without pretension inside. Next to section size selection of the stiff system according to stress check or deflection control or stability capacity ability, it is needed to do shape determination analysis of lower cable-bar system on the basis of reaction forces in vertical direction due to gravity load, i. e., 1.0 times of dead load including self-weight of the stiff beam members and appended roof covering materials.

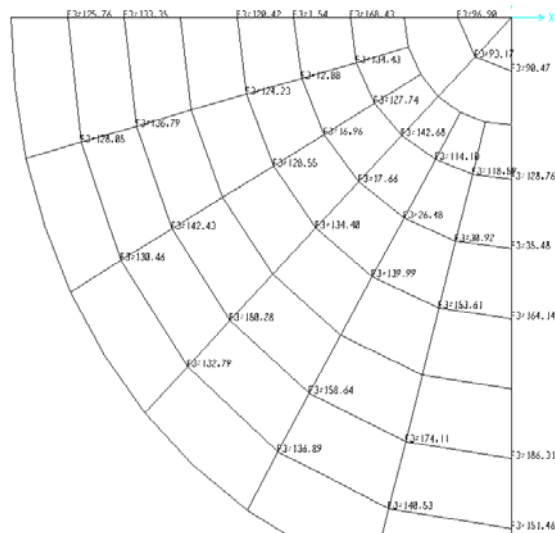## 2.3   Shape Determination Analysis of the Lower Cable-bar System

Shape determination analysis is conducted utilizing computational algorithm put forward in the reference [10]. That computational algorithm is universally available for hybrid spatial structures by using Model A and Model B. These two models differ with each other on the boundary conditions. Dynamic relaxation method and local analysis method are combined for a stable surface shape finding of the lower node positions of paunch bars and cables. Figure 12b gives out the final shape of the lower cable-bar system. The main difference between Figure 12a and Figure 12b lies in the hoop cable spatial shape. An adaptive cable-bar system contains a spatial hoop cable on a saddle-like surface to provide necessary support for upper single-layer reticulated shell.
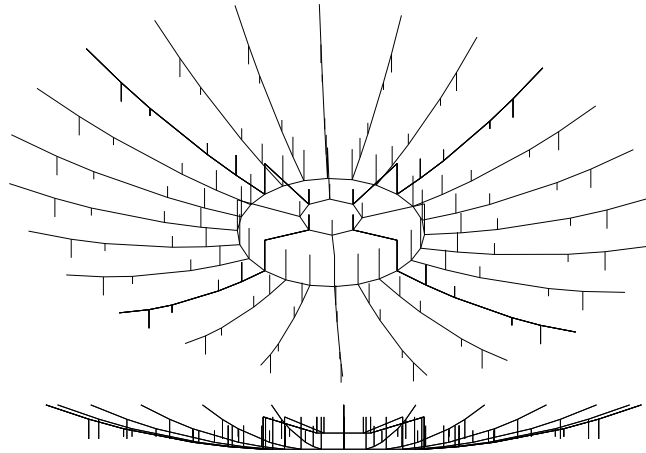
(a) Rough Shape of the Lower Cable-bar System
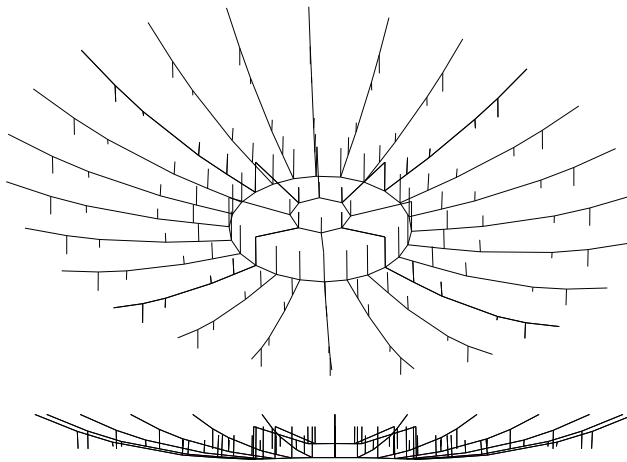
(b) Final Shape of Lower Cable-bar System after Shape Determination Analysis

(c) Reaction Force in Vertical Direction/kN

Figure 12. Shape Determination Analysis of Lower Cable-bar System

Figure 12c is the reaction force in vertical direction from the stiff system under dead load. For precise shape determination analysis of lower cable-bar system it is needed to take account of the self-weight of the cables and bars. Iterative work from Figure 12b to Figure 12c is indispensable. After shape determination analysis of lower cable-bar system the pretension level and distribution are obtained at the same time. Then, it is easy to select proper sections of cables and bars. Table 1 gives out the final section size of each member. Table 2 shows the final pretension level and distribution of lower cable-bar system. Figure 13 is the element number of a quarter of lower cable-bar system.

Table 1. Section Size of All Members

| Member name	Section size	Material/standard breaking capacity ability
V-shaped inclined column	P900×25	Q345B
Steel column between ringbeams	P900×25	Q345B
Upper ringbeam	P1700×35 with C40 concrete inside	Q345B
Lower ringbeam	P1000×30	Q345B
Paunch members between ringbeams	P325×12	Q345B
Radial beams of outmost ring	B900×400×30×30	Q345B
Other radial beams	B600×400×16×20	Q345B
1st ring members	P219×8	Q345B
2nd and 3rd ring members	B600×400×16×20	Q345B
4th -7th ring members	P273×10	Q345B
8th ring members	P402×14	Q345B
Brace pipes	P273×10	Q345B
Outer diagonal cable	Φ7×151	1770MPa
Outer hoop cable	Φ7×421	1770 MPa
Paunch cables	Φ7×13	1770 MPa
Inner diagonal cables	Φ7×19	1770 MPa
Inner hoop cables	Φ7×31	1770 MPa
Outer paunch bars	P219×8	Q345B
Inner paunch bars	P114×8	Q345B
Appended cables for purpose of circular stability	Φ7×13	1770 MPa
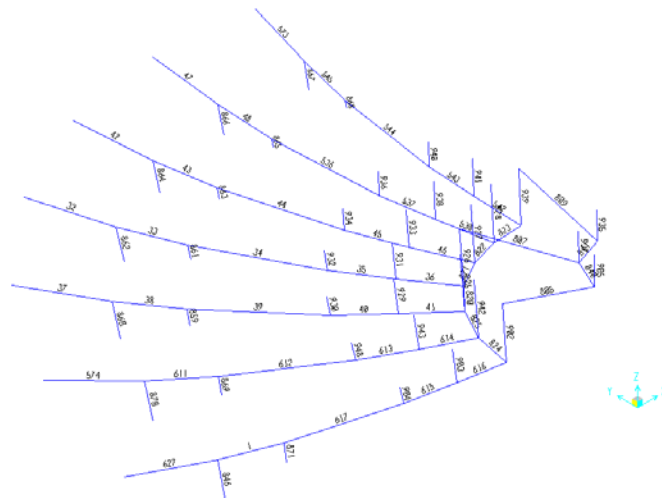
Figure 13. Element No. of 1/4 of Upper Single-layer Reticulated Shell

Table 2. Pretension Distribution of Lower Cable-bar System

Element No.	Pretension/kN	Section size	Element No.	Pretension/kN	Section size
627	1826	Φ7×151	807	306	Φ7×19
1	1788	Φ7×151	809	296	Φ7×19
617	1761	Φ7×151	840	389	Φ7×31
615	1725	Φ7×151	841	386	Φ7×31
616	1725	Φ7×151	846	126	Φ7×13
574	1800	Φ7×151	871	134	Φ7×13
611	1760	Φ7×151	870	128	Φ7×13
612	1729	Φ7×151	869	137	Φ7×13
613	1696	Φ7×151	860	130	Φ7×13
614	1693	Φ7×151	859	142	Φ7×13
37	1747	Φ7×151	862	133	Φ7×13
38	1705	Φ7×151	861	150	Φ7×13
39	1671	Φ7×151	864	137	Φ7×13
40	1644	Φ7×151	863	159	Φ7×13
41	1642	Φ7×151	866	141	Φ7×13
32	1692	Φ7×151	865	175	Φ7×13
33	1649	Φ7×151	867	152	Φ7×13
34	1610	Φ7×151	868	189	Φ7×13
35	1590	Φ7×151	904	-121	P219×8
36	1588	Φ7×151	903	-2	P219×8
42	1631	Φ7×151	902	-269	P219×8
43	1585	Φ7×151	948	-125	P219×8
44	1540	Φ7×151	943	-13	P219×8
45	1526	Φ7×151	942	-134	P219×8
46	1525	Φ7×151	930	-129	P219×8
47	1609	Φ7×151	929	-17	P219×8
48	1559	Φ7×151	925	-128	P219×8
536	1507	Φ7×151	932	-135	P219×8
537	1497	Φ7×151	931	-18	P219×8
538	1496	Φ7×151	926	-235	P219×8
573	1643	Φ7×151	934	-140	P219×8
545	1586	Φ7×151	933	-26	P219×8
544	1509	Φ7×151	927	-114	P219×8
543	1501	Φ7×151	936	-154	P219×8
542	1500	Φ7×151	938	-31	P219×8
824	6083	Φ7×421	928	-119	P219×8
825	6079	Φ7×421	940	-165	P219×8
820	6072	Φ7×421	941	-36	P219×8
821	6060	Φ7×421	939	-218	P219×8
822	6054	Φ7×421	905	-97	P114×8
823	6048	Φ7×421	937	-93	P114×8
805	336	Φ7×19	935	-90	P114×8

After these work in Section 2.1 and Section 2.2 constituting system is finished. Next is to do load/action effects analysis according to national code of practices.

3.   LOAD/ACTION EFFECTS-MEMBERS' SECTION DESIGN

In general, structural performance denotes a structure or an assembly behaves well (safe/stable, comfortable, reliable) when subject to possible loads/actions during its lifecycle. Performance based design needs the designer to preset or adjust the structure mechanical property, wind induced response, acceleration and so on by modifying the structural type, member section, or boundary conditions.

3.1   Load/action Conditions

Load/action conditions are one of the most important conditions of practical structural design. In the current Chinese load code of practice load/action and their corresponding combinations are given out and specified in details. The standard value of load/action is based on statistical analysis of materials, meteorological record of wind speed, snow, temperature, earthquake and so on. Standard value of dead load is 0.60kN/m^2. Standard value of live load is 0.50kN/m^2. Basic wind pressure at the height of 10 m with a return period of 100 years is 0.70kN/m^2. Snow load with

return period 100 years is 0.40kN/m^2. Temperature change is considered from +25℃ to -25℃.

Seismic load is not significant at the construction site.

Load analysis is based on the current code of practice of structural design. Many load combination cases can be analyzed. Geometrical nonlinear analysis is necessary. The results may be checked automatically with respect to the maximum deflection (Table 3) and the maximum stress ratio of members (Table 4).

3.2   Verification in Ultimate Serviceability Limit Sstates

From Table 3 it is shown that Dead + wind load case gives rise to the largest nodal displacement. Displacement to span ratio is 1/406. Semi-span live load is more dangerous than uniformly distributed live load. Temperature effects are not significant. This is rational for a self-equilibrated structural system.

Table 3. Maximum Deflection

Load cases combination		Maximum deflection/mm	Direction
1	Dead	-28.8（1/4444）	downward
2	Dead + Live	-147.4（1/868）	downward
3	Dead +Upper semi-span live	-273.4（1/468）	downward
4	Dead + Left semi-span live	-211.5（1/607）	downward
5	Dear + Temperature rise	-46.8（1/2735）	downward
6	Dead + Temperature decrease	-76.1（1/1681）	downward
7	Dead+Wind	315.3（1/406）	upward

3.3   Verification in Ultimate Load-carrying Capacity Limit States

Table 4 is the maximum stress ratios of each member under possible load cases combination. Stress ratios of beam element do not exceed 0.9. The maximum internal forces in cables do not exceed 50% of their breaking stress. Stress check of upper steel ringbeam does not consider the contribution of concrete materials.

Table 4. Maximum stress ratios

Section size	Stress ratio
P1700X35 with C40 concrete inside	0.37
BOX600X400X16X20	0.70
BOX900X400X30X30	0.68
P1000X30	0.21
P114X8	0.43
P219X8	0.58
P273X10	0.55
P325X12	0.66
P402X14	0.49
P900X25	0.39
Φ7X13	0.42
Φ7X151	0.34
Φ7X19	0.43
Φ7X31	0.31
Φ7X421	0.41

This section only summarizes strength and deflection results under possible load cases. Other structural performance such as modal analysis, wind-induced vibration analysis, nonlinear geometrical stability analysis, construction sequence simulation, and so on will be discussed in details in other papers.

4.   JOINT DESIGN

Joint design needs careful FEM analysis using solid element. Joints should be designed with enough strength, stiffness, and reliability. Second, joints should not break before cable breaking. Third, joints' deflection should not affect the structure mechanical property. A special joint when diagonal cable penetrating the upper corresponding beam member is put forward in Figure 14. The advantage of this joint design lies in its water proof function which is very important for architectural design.
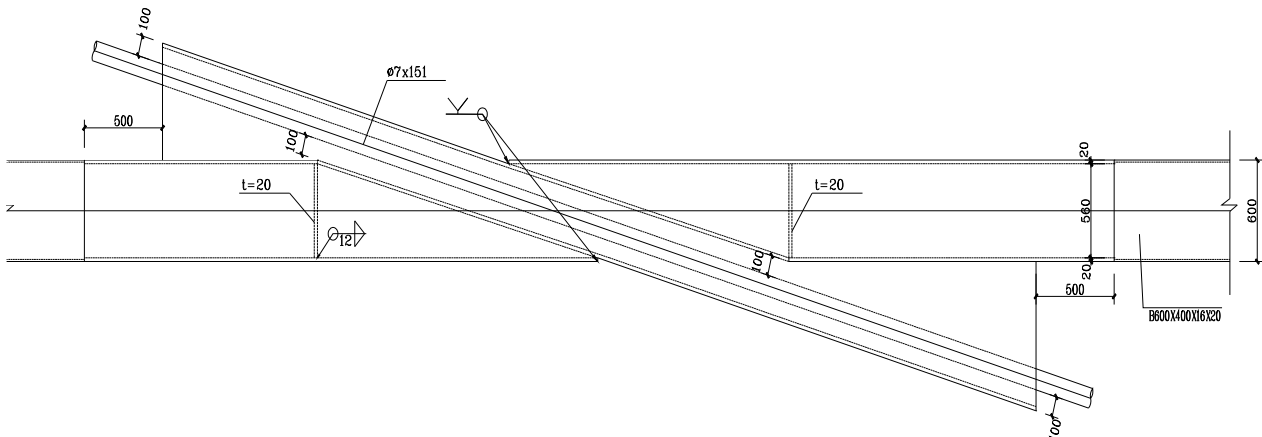

Figure 14. Diagonal Cable Penetrating Upper Steel Beam Joint

5.   CONCLUSIONS

A novel large-span cable-frame type of suspended single-layer reticulated shell with free surface is presented in this paper. Emphasis is put on the structural system constitution including form finding of the upper structure and shape determination analysis of the lower cable-bar system. Load/action effects are thoroughly summarized for member sections design. A special joint design when diagonal cables penetrating corresponding upper steel beam is presented.

The key problem of shape finding analysis of lower cable-bar system is of most importance. This algorithm that combines local analysis method and dynamic relaxation method is universally available for general hybrid spatial structures. Further work on more precise shape determination analysis composed of upper and lower structures is needed.

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