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Research on Structure Analysis and Design Optimization of Lamella-Kiewitt Suspend-Dome

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ABSTRACT :*In this paper, the consideration of system selection of long-span steel structure, and the structural analysis and design optimization of Lamella-Kiewitt suspend-dome were studied. The first part of this paper summarized and classified all kinds of the long-span spatial steel structure system, and their main structural features, development, and application, advantages, and disadvantages were briefly introduced. Selecting the feasible system was considered based on architecture, structure, economy, and buildability index. The Lamella-Kiewitt suspend-dome is selected as the roof structure, and the static performance of the structure is obtained by nonlinear geometric static analysis, the eigenvalue analysis is carried out by subspace iteration method, and the response spectrum analysis is adopted for dynamic analysis of the structure. The axial stress in cable-strut, the overall deflection of the roof structure, and the natural frequency were satisfied with the Chinese design code. The structural optimization of the roof structure is studied under the various rise-to-span ratio, strut-height, and single-layer reticulated shell types. Analyses and optimization of suspend-dome in the paper were conducted with finite element software Midas Gen. From the result of optimization show that the total steel consumption of Lamella-Kiewitt single-layer suspend-dome structure with four hoop cables has a good economy. The study of this paper can provide a reference for the construction of a similar structure in the future.*

KEYWORDS *Steel structure, Large span, Lamella-Kiewitt single-layer reticulated shell suspend-dome, Finite element analysis, Structural optimization*

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I. INTRODUCTION

In the preliminary stage of planning a roof to cover a specific building, several factors should be studied and evaluated before proceeding to structural analysis and design. Choosing the general form of the building and the types of large-span spatial structures appropriate to this form need to be studied carefully in the light of various pertinent requirements. The geometry of the structure is an important factor to be planned, which will influence both the bearing capacity and the weight of the structure. The satisfying of reasonable stress, durability, reliability, and consume fewer budgets are advanced in the structural selection, but in addition to these, well connecting the structural technical performance with the artistic modeling allows the self-expressiveness of the building [1].

The development of modern large-span space structures in China and their applications were classified into three groups as a modern rigid, flexible, and rigid-flexible space structure [2]. Among those three groups, large amounts of rigid-flexible structural systems have become the main keys in the application and development of large-span space steel structure. The strong evidence of the recent development of large-span space structure in China can be found in the construction of the 37 stadiums and gymnasiums for Beijing 2008 Olympic, where the brilliant concepts for both structure proposals and construction techniques were exhibited into the real projects [3].

Suspend dome structure can achieve its self-balance system by the introduction of a cable-strut system to a single-layer reticulated dome. The concept of the first suspend dome was created in the 1990s by professor Mamoru Kawaguchi et al. Hikarigaoka Dome which was the first suspend-dome in the world was built in Japan in 1993, and the first representative application of suspend-dome in China is the hall of the service business center in the Baoshui of Tianjin. The internal force of a single-layer latticed shell could be reduced with the introduction of lower cable-strut [4], and the model test on a small-scale suspend-dome which was conducted by

Kawaguchi et al [5] indicated that the stability and the rigidity of the structure has been improved greatly compared with the single-layer latticed shell. Zhang et al. [6] noted that weak boundary bearing capacity system becomes possible usage as the self-equilibrated system of suspend-dome which the internal force flow could be built in a closed loop. A comparison of the construction difficulties of suspend-dome is lower than the cable dome which was mentioned in an experimental model study of tension schemes by Dong et al. [7]. Kitipornchai et al. considered prestressing procedure methods and the intensive analysis of nonlinear buckling under various conditions as the factors that affect the analysis and erecting of the Lamella suspend-dome [8]. The simulation of the pretension process in suspend-dome using a sequential analysis method based on the initial cable deformation and multi-stages pretension scheme provides an accurate result as the expected initial state [9].

The Lamellar-Kiewitt single-layer suspend-dome is one of the suspend-dome types and was named after the Lamellar and Kiewitt reticulated shell was successfully combined and adopted as the rigid shell. To ensure the structural safety, members stiffness, rigidity, and more economic, the structural design analysis and optimization based on structural morphological parameters will be conducted thoroughly.

II. TYPICAL CLASSIFICATION AND APPLICATION OF LARGE SPAN STEEL STRUCTURE

1. Classification of Large Span Steel Structure

There are four methods in classification of large span steel structure based on 1) structure form (shell structures, space truss structures, reticulated shell structure, suspension structure, and membrane structure), 2) characteristics of forces (rigid, flexible, and rigid-flexible structures), 3) the structural elements (FEM), and 4) the mechanical criteria (axial force and moment structures). The basic structural elements of the large-span structure are divided into two categories as their calculation method and finite element analyses: rigid element (plate, shell, beam, and bar elements) and flexible element (cable and membrane elements). Large span space structures are composed of one, two, or three structure element types, and there are 38 types of space structural system in the world [10].

2. Application of Large Span Space Structure in China

Since the early of the 21st century, the development of both the indoor and outdoor sports activities in China has vigorously increased, and sports facilities have been modernized across the country as the Summer Olympic was going to be held in Beijing in 2008, and another successive win new bidding to host for the first time of the Winter Olympic in Beijing in 2022. To fulfill the Olympics sports requirement, many stadiums and gymnasiums were built as for the competition venues, for example, Beijing National Stadium (Bird's Nest), Beijing National Aquatics Center (water cube), Beijing National indoor stadium and Beijing Institute of Technology Gymnasium. Their structural roof systems were built with full the challenge in architecture aesthetics and engineering by adopting new technologies, structural forms, and construction techniques. The increase in demand for large covering roofs for airport terminals, train stations, halls, and exhibition centers have also decisive influence on the rapidly developed large span steel structure.

The modern construction technologies such as high-strength cable and construction industrialization, the challenges in new architectural concepts, and building features requirement are the influent factors on the development of large-span structures which were made mainly in two ways: form-based innovation and combination-oriented innovation. The innovation of new structural systems provides better structural performance, higher rigidity, lighter structural weight, lower construction difficulties, and more economic.

The structural characteristic and behavior of commonly adopted structure systems such as spatial grid, space truss, beam string, suspend-dome, arch structure, and retractable roof structure are summarized and followed by their application in the gymnasium in China (see Tab.1).

Space Frame Structures: The structure of a space frame is a highly redundant structure and force distributes in a three-dimensional state. It has very large stiffness to resist the unsymmetrical or heavy concentrated load, while its versatility of shape and form is flexible to the required building geometry. The invention of several new connecting methods of the proprietary system has made a great improvement in the construction of the space frame. However, a large burden of the support is required to reduce thrust and satisfy the roof deflection [11]. Double-layer grids are the most commonly adopted system among the space frame structures.Shenyang Tiexi Sports Center (71.6m×89.7m), adopted a 2m height of a two-way reticulated shell (54kg/m^2). MSTCAD of Zhejiang University was used to optimize the members of the reticulated shell (Fig.1). Fujian Provincial Gymnasium has an irregular roof shape of 112m span (7,800 seats) where a flat spherical double-layer reticulated shell with thickness 3m was used.

Truss Structures:Truss structure in the form of planar truss and space truss (three-dimensional truss) is one of the most commonly adopted large-span structures in roof systems. The load is applied as the nodal load while only axial force is existing in truss members. In the analysis of structural system engineers frequently performed by assuming all nodes joints are idealized pinned or rigid joint, and eccentricity of the intersecting members at joints should be kept within the allowable range. The steel truss system has great stiffness and lateral strength meet the construction convenient such as easier to hook up and more stable to erect. Type of connection of truss has much influent on truss analysis and design especially on construction process, cost, time, and structural rigidities.The roof of the Gymnasium of Sports Center in Shache Teaching Park adopts 15 petal shape spatial steel pipe trusses to form a blooming almond flower, and the oval in the plane roof with dimension 125m×100m can accommodate 3,700 audiences (built 2014). Gymnasium of Haihu Sports Center is one among three of blooming snow lotus, stand on the beautiful Qinghai-Tibet Plateau; circular with a diameter of 112m and capacity 7,500 (built 2009), the roof structure adopts a rib-ring space truss in the inner area of the steel roof through economic and technical comparisons of various structural systems, and architectural requirements (Fig.2).

Beam String Structures:Beam string structure (BSS), which is a new kind of semi-rigid hybrid system, composed of arch, strut, and string, and has been developed rapidly in recent years with a span larger than 80m. It is the self-balanced structure that evolved basically from truss and was proposed by Saitoh in the1980s. The prestressing process of BSS has a very big influence on the overall stability of the structure. To acquire the reasonably stressed-state of structure, the principle of multi-stage analysis and design for tensioning and loading process should be employed. To ensure the out-of-plane stiffness of planar and spatial beam string structure, the bracing system should be adopted in the roofing system. BSS has various types such as one-way, two-way orthogonal, and multi-way beam string.The roof of the gymnasium of Quanzhou Straits Sports Center adopted one-way spatial beam string structure with a maximum span of 94m, has 8,000 capacity (built 2008); seven parallel triangular space trusses with a height of 3m and width 2m were braced by the inclined tension rod and strut at each 12m space (Fig.3). Qinshui Public Fitness Center has 5,925 capacity, ellipsoidal roof with dimension 130.7m×106.1m, and 31.4m height whose façade was combined by the metal panel and glass. The BSS which is arranged in the short direction has 3 struts with a maximum length of 3.5m, and the lateral stiffness was stiffener by the secondary beam.

Suspend-dome Structures:Suspend dome structurecan achieve its self-balance system by the introduction of a cable-strut system to a single-layer reticulated dome. The prestressed cable can vary the value and distribution of stress in the whole structure, thrust forces are significantly reduced, and the stiffness of the structure is increased. Prestress can be done by applying tension in hoop cable or inclined rod or by lengthenable the strut. A circular projection plane is often adopted in suspend dome; however, ellipse and polygon can also be adaptable.The largest suspend dome in the world located in China since 2008 as Jinan Olympic Sports Center (13,000 seats) and Dalian Gymnasium 2014 till now (18,000 seats). Beijing University of Technology Gymnasium is 141m×105m (max-span 93m), was built in 2007, and steel consumption 60kg/m^2 (10,076 seats). The roof of Jinan Olympic Sports Center Gymnasium adopted a three-loop spherical rib-ring suspend-dome using the mixed arrangement of Kiewitt and sunflower rigid shell, round with max-span 122m (Fig.4). Gymnasium of Jining Sports Center (5,624 seats) built-in 2014, suspend dome adopted in the large span roof of the central competition area as corner quadrilateral (70m×99.6m).

Arch Structure:The arch structure can be subdivided into arch-hanging and arch-supporting structure depending on the relative height of the arch and roofs, position, and connection of the arch. The arch structure generates a large horizontal thrust at the support, thus increasing the burden on the lower supporting structure. The horizontal thrust of the support arch should be minimized.Fudan Zhengda Gymnasium, an elliptical shape 82.1m×101.6m, which adopted steel truss cable-arch as a giant steel arch spanning 100m across the roof stand with an angle of 76º to the horizontal plane, and accommodate 5,000 people (in 2005). Three-dimensional truss was selected as the main skeleton with three different cable categories: the stressing cables, the stabilizing cables, and fly rods cables. Beijing Institute of Technology Gymnasium, a flat hyperbolic paraboloid (90.8m×86.5m, 28.2m height), adopted two space curve arches as the main load-bearing structures, both arches were connected by three-dimensional frame, while inverted triangle 3D frames were hung below and sliding bearing was used (Fig.5).

*Retractable Roof Structure:*The retractable roof can be opened under good weather condition and closed if the weather is unfavorable as it can transform geometrically between two distinct configurations. The translation or rotation of the large-rigid element is often in form of overlapped or folded and the method of opening and closing can be classified according to the direction of the roof movement and the method of stowing the retracted roof. Structural analysis and design of retractable roof which is relatively novel mainly depending on the type of structural system of steel roof being used as canopy and method of opening and closing. The structure required to analyze under 3 states: fully closed locked state, fully open the locked state, and motion.The retractable roof of Shanghai Qizhong Tennis Center which was built in 2005 (circular, span 144m), is the world’s first in many aspects such as structure scale, cantilever size, opening mode, and opening effect. It can accommodate 15,000 people. The roof adopts the space curved surface shape of the magnolia leaves (8 pieces). The design and construction of the roof structure and mechanical transmission system have great innovation and challenge (Fig.6).

Table 1. Application of large span space structure in the gymnasium in China

Project Name	Scale/(m^2; *seats*)	Plane size	Structure	Completed in
Dalian Gymnasium	83 000/18 000	Circular;145.4m×116m	Lamellar-suspend-dome	2014
Gymnasium of Jining Sports Center	24 215/5 624	Ruby shape; 168.6m×92.4m	suspend-dome+ BSS	2014
Gymnasium of Changshu Sports	28 450/ fix: 4 100, movable:1 800	Conch, spherical shell; 90.4m×81m	Suspend-dome+ plane steel T-truss; 75kg/m^2	2012
Jinan Olympic Sport Center Gymnasium	60 300/13 000	Circular;220m×168m, max-span 122m	3-loop spherical rib-ring suspend-dome	2008
Anhui University of Gymnasium	12 000/5 000	Hexagon-diamond shape; 87.7m×87.7m	Suspend-dome+ single-layer latticed shell	2008
Beijing University of Technology Gym-	34 383/10 076	Ellipse; 141m×105m, max-span 93m	Dome string+ Prestressed suspension-dome; 60kg/m^2	2007
Shenyang Tiexi Sports Center Gymnasium	12 300/fix:3 000 moveable1000	Ellipse; 89.7m×71.6m	Double-layer grid, mesh 6m×6.9m×3.5m ;54kg/m^2	2008
Fujian Provincial Gymnasium	23 915/7 800	Flat sphere; Dia-112m, max-span 91.9m	Double-layer spherical reticulated shell, *f/L:* 1/10	2002
Chifeng Sports Center Gymnasium	25 000/8 000	Half-circular& octagon; 96.6m×103.2m	Two-way orthogonal grid, 6.7m grid height	2013
Ningbo Olympic Sports Center Gymnasium	47 449/12 678	Ellipse; 225m×130m	Two-way plane truss; 52kg/m^2	2018
Gymnasium of Haihu Sports Center	23 273/7 500	Circular shape; Diameter 112m	Rib-ring space truss+ single-layer grid	2009
Shache Teaching Park Gymnasium	16 900/3 700	Oval shape; 125m×100m	Long-span steel truss	2014
Shanghai Jiaotong University Minhang	----/8 000	Ellipse; 119m×63m	Steel arch + membrane structure	2007
Peking University Khoo Tech Puat Gymnasium	26 900/ fix:6000 movable 2000	Chinese Ridge; 93.2m×72m	Prestressed truss shell	2007
Gym-of Shanghai University of Science &Technology	11 086/2 280	Oblique ellipse; 87.5m×47.5m	Backbone beam string structure	2015
Qinshui Public Fitness Center Gymnasium	40 188/5 925	Ellipse/Gem shape; 130.7m×106.1m	Beam string structure	2012
Beijing Institute of Technology Gymnasium	21 882/ fix:3700 movable 1300	Hyperbolic; 90.836m×86.57m	Double-arc arch steel truss	2008
Fudan Zhengda Gym-	12 318/5 000	Ellipse; 82.1m×101.6m	Suspension arch 100m span	2005
Shanghai Qizhong Tennis Center	65 000/15 000	Blooming Magnolia flower; Dia-144m	Removable roof, 8 main steel trusses blade roof	2005

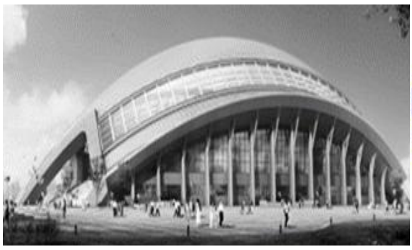


Fig.1 Shenyang Tiexi Gymnasium

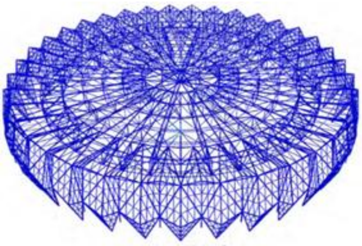


Fig.2 Gymnasium of Haihu

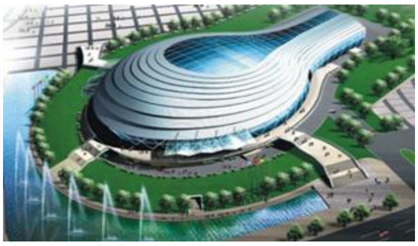


Fig. 3 Gymnasium of Quanzhou

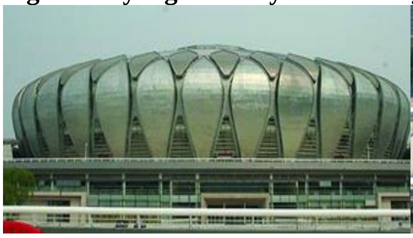


Fig. 4 Jinan Tiexi Gymnasium


Fig.5Beijing Institute of Technology Gym


Fig.6 Shanghai Qizhong

3. *Consideration of the Structural Selection*

As mentioned earlier, choosing the appropriate structure types will result in a direct influence on the overall cost and speed of construction. Structural system selection and design of large span spatial structure should focus on solving the morphological problem. While architectural design should be realized through structural matters and the application of structural forms, the material should be used, architectural space, volume, and shape play a decisive role. The direct integration of the architects and engineers is to form a basic structure that solves this problem and reflects the perfect combination with structure beauty, providing a good choice for structural system, and the structural concept becomes opened and diversified. The consideration of system selection of large span steel structure roof is usually conducted on the basis of the four most important indices. They are architectural suitability, structural rationality, economy, and buildability index. In this study, the Lamellar-Kiewitt single-layer reticulated shells suspend-dome was determined as the feasible structure for a medium-sized gymnasium with 92m span through the above four factors.

Architectural suitability: the rigid shell of suspend-dome adopted single-layer braced dome in form of Lamellar mesh pattern, which was modified into Kiewitt 8 at the roof center in order to prevent from an uneven mesh. This modified structural layout arrangement has a sense of rhythm, strength, visual beauty, and impressive simplicity of lines in a single-layer. The upper single-layer shell is attached to roofing material, and the lower cable-strut system is simple, light, clear power transmission, and smooth atmosphere on the vision. Its applications are found mainly in a circular projection plane that benefits the indoor sports building especially the gymnasium, see table 1.

Structural rationality: suspend-dome is a hybrid structure where the existing of high strength cable, and the prestressed value has much influent on improving the structure stiffness and stability, especially reduce the axial force in rigid shell components. The structure is lightweight due to material distributed spatially and all material in any given element is utilized to its full extent. The cable-strut forming continuously closed loop in circular projection plane can give full play to each component respective corresponding role, and applied tension force is the same everywhere in the same ring that would improve the construction difficulties and reduce the burden on the lower frame thrust support. The structural design safety is the primary objective that requires a detailed analysis, fully understand the structural system of the safety reserve.

Economy: For the long-span spatial roof, the most direct index cost is the amount of steel in a one-meter square. The suspend-dome structural system is the lightweight structure which the amount of steel consumption is significantly decreased compared to other systems, for example, the comparison between single-layer reticulated shell, double-layer reticulated shell, and suspend-dome in Changshu Sports Center Gymnasium showed the amounts of steel consumption vary respectively as 95kg/m^2, 85kg/m^2 and 75kg/m^2 [12]. The horizontal burden on support was decreased hence the less support cost.

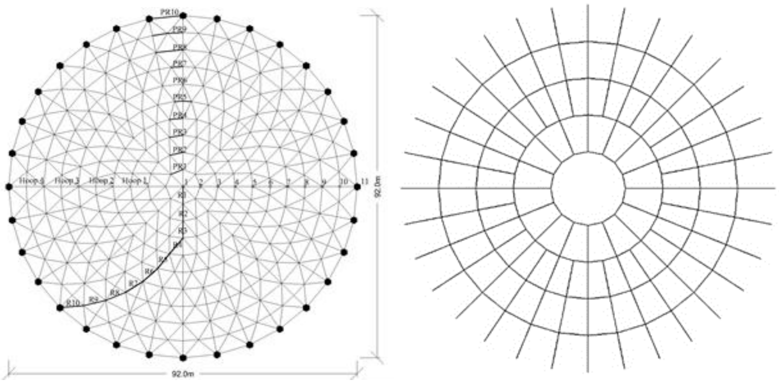
Buildability: The fabrication costs usually share 30-40% of the overall expenses, which is largest portion taken from the assembly of joints. To obtain faster construction and better ductility and toughness, cast steel hollow spherical tube joints were adopted instead of welded hollow ball nodes joints. Different welding seam positions might minor the construction difficulties such as welding space, assembling members, and speedy welding procedure. The structure can take full advantage of the industrialized system of construction (prefabricated units, standard-sized and shape, easily transports and rapidly assembled on-site by semi-skilled labor) and build at a lower cost. In general, difficulties in manufacturing and assembling of structural components can increase the cost of the new structural parts and face the installation problem. In order to component modeling beauty and processing technology and economic balance, the constant optimization of the system should be applied in the design stage.

III. STRUCTURAL ANALYSIS OF LAMELLA-KIEWITT SINGLE-LAYER RECTICULATED SHELL SUSPEND-DOME

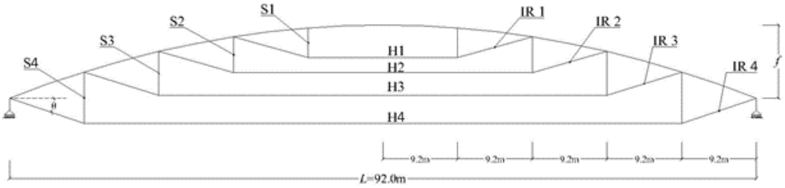
1. Structural Geometry and Modeling Parameters

The Lamellar-Kiewitt single-layer reticulated shell suspend-dome was selected as the roof of the medium-sized gymnasium with approximately 4000 capacity. The structural design life of the project is 50 years, the safety factor is the first level, and the structural importance coefficient is γ=1.1. The plan projection is perfectly circled with a diameter of 92m, the highest elevation at the central roof is 30m and roof height is 9.20m which is equivalent rise-to-span ration of 1/10. This rise-to-span ratio of the roof is categorized as a large-span small-rise-to-span ration flat shell. Four rib-ring hoop cable and inclined rods have the same interval space of 9.20m, see Fig 2. The steel pipe of single-layer shell adopted cast spherical ball node joints and radial members size ϕ194×5 to ϕ273×8, ring members ϕ121×4 to ϕ273×7 and struts ϕ121×4 to ϕ203×6 have yield strength of 345MPa. Hoop cable and inclined rod members respectively have yield strength of 1860MPa and Q460 with the maximum member diameter of ϕ110mm. Prestressing forces are prestressed from outermost ring to inner ring on hoop cable are 3122kN, 1190kN,475kN, and 156kN, and inclined rods are 642kN, 287kN, 125kN, and 75kN.

The structural model was established by using the finite element analysis software Midas Gen, beam, and truss elements are respectively used to simulate single-layer members and struts. The radial inclined rods only support tensile forces; therefore, simulations are performed using tension-only truss element, while hoop cables which are flexible structures that lost stiffness and bearing capacity under compression are simulated by tension-only cable. The constraint condition of the roof to the lower support structure is a three-ways hinge, and all nodes of the single-layer shell are rigidly connected.



(a) Single-layer reticulated shell (b) Cable-strut system



(b) Section-view of the roof

Fig. 7 Member arrangement of the roof structure

2. *Load Action*

Self-weight is calculated by the program. The dead load DL=1.50 kN/m^2 is applied as the sum of loads of purlin, roof panel system, maintenance horsing trolley and hanging equipment, etc. Live load LL=0.50 kN/m^2 is adopted. Based on the Load Code for the Design of Building Structures GB50009-2012, appendix E.5, for the design reference period of wind load of this project is 100 years, the ground roughness is C, the basic wind pressure w_0= 0.50 kN/m^2, the variation coefficient of wind pressure height μ_z=1, coefficient of wind vibration β_z=1.76, wind factor for the roof (μ_s): f/L=0.1, both are wind suction effect with value μ_s= -0.8 (windward) and μ_s= -0.5 (leeward side). Uniform snow load (SU) and non-uniform snow load (SNU) is considered with basic snow pressure S_0=0.45 kN/m^2 (n=100years). Temperature effect on steel roof was considered with initial temperature 20℃ with 45℃ heating up and -15℃ cooling temperature; excluded interior members which are the temperature taken as 30℃ for heating up and -5℃ for the cooling condition.

The relevant provisions of load combination considered when performing structure analysis under serviceability limit state, bearing capacity limit state with no earthquake, and with earthquake totally 65 load combinations are included in this study. All the static load combinations are converted into static load cases to perform geometry nonlinear static analysis for a structure where the presence of nonlinear elements like a cable.

3. *Static Analysis*

In the analysis of the structure containing cable elements, nonlinear analysis is needed to perform static analysis. The static equilibrium equation of a structural system contains nonlinear element can be written as follow: $[K+K_N]\{U\}=\{P\}$(3.1)

K= Stiffness of linear structure and K_N=Stiffness of nonlinear elements

The nonlinear stiffness K_N can be found by modifying the loading term and keep the stiffness term unchanged.

$$[K+K_L]\{U\}=\{P\}+[K_L-K_N]\{U\} \qquad (3.2)$$

K_L=Stiffness of nonlinear elements at the linear state

For tension-only truss, the nonlinear stiffness is expressed as in (Eq.3.3)

$$K_N=f(D-d) \qquad (3.3)$$

D=Initial distance and d= change in member length resulting from the analysis

Geometry nonlinear static analysis employed Newton-Raphson Iteration method to obtain the axial force, reaction and displacement. The total number of load step 20 with the maximum number of load step 100 and the convergence tolerance 0.001 for displacement norm and work norm are considered in the analysis. The maximum reaction force in the vertical direction F_z=678kN under 1.35*DL*+0.98*LL* load combination; horizontal reaction force -249kN in both direction as the result of load combination of earthquake in X and Y direction. The initial pretension was applied as the initial stiffness of cable member for the lower cable-strut system. The value of initial tension was considered carefully by the following conditions: (1) initial tension creates the vertical deflection as small as possible under the load combination 1.0*DL*+1.0*LL*; (2) applying pretension in the safety reserved region which is not over than 65% of the cable breaking strength f_u. The maximum stress ratios of steel members are not larger than 0.8.The axial force results of cable and inclined rod members decreased from outer to inner ring, while the maximum axial tensile force happens under the load combination effect of 1.2*DL*+0.98*LL*+1.4 *T-cooling*. When the value of prestressing force in cable increases, the axial strut force also increased, it shows clearly interaction of cable-strut system components in order to adjust the stiffness to resist to any applied loads.

The graph of moment increases significant at the radial and circumferential members between ring 1 to ring 3, the graph of gCBL9 and gCBL31which are almost the same, show the structure having extremely large positive moment (Fig.8). The cooling temperature load exists in these both load combinations, while load combination gCBL8 created large negative moment where the heating temperature is included in the combination. The graph continue indicates that central radial diagonal and circumferential ring member are playing more important role in resisting moments, while circumferential ring members which located between each strut-supported, resist the minimum moment. Under all working load conditions, the maximum deflection of the structure is -206.9mm (less than 1/400, *L*=92m) which is satisfied stiffness requirement by the technical specification of space frame structure JGJ7-2010. The significant deflection of roof happens in the central region where the lower cable-strut are not presented, by improving the single-layer stiffness like increasing the member section or rising ratio of shell.

4. *Dynamic Analysis*

The eigenvalue analysis using the subspace iteration method is employed for linear static analysis of the gymnasium roof structure in order to obtain the structure's mode shape and its natural vibration characteristic values. The convergence tolerance 1e-006 with the number of iterations of 20 is set in the eigenvalue analysis control parameters. Cable element will be changed into truss element in eigenvalue analysis as mentioned in Midas Gen manual. Therefore, in order to perform eigenvalue analysis of cable members, tension forces are applied in form of initial element forces with small displacement in Midas Gen. Moreover, the zero-state load case has been included into all the load combinations after the initial force has been added to element force for that load case.

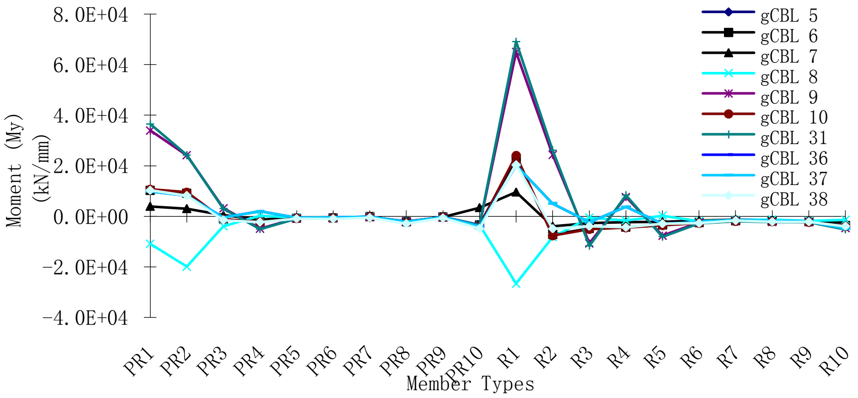


Fig. 8 Moment of single-layer reticulated shell members

Dynamic of the gymnasium was studied using modal response spectrum analysis, and the modal combination adopted complete quadratic combination (CQC) method. The first mode shape having the smallest natural frequency which is 1.57H_z>1H_z; satisfied the design code. The first 4 mode shapes are the rotation of hoop cables in Z-direction, due to flexibility of the lower cable-strut system where the rib-ring layout was adopted in the system. For the 5th and 6th mode shape, the natural frequency and vibration period are almost respectively the same for these two modes. The structure's mode shape from the 5th order appears as a superposition of horizontal and vertical direction, and the form of vibration is more complicated. From mode 7th, in order to vibrate the structural roof system requires the higher energy or force and the structure becomes stiffer. The higher-order modes also have a twist, and the structure's natural frequency distribution is large, and its vibration form is complex. In order to ensure that all the critical mode shapes that affect the results are included in the analysis, the number of mode shape with the sum of total of modal mass participation greater than or equal to 90% was obtained (from mode shape 28 up). The major mode of directional modal participation mass is the displacement in x-direction MPM=66.833 (6th mode), displacement in y-direction MPM=66.809 (5th mode), and rotation in z-direction MPM=46.378 (7th mode). Moreover, the displacement of modal coordinate in response spectrum analysis also indicated that mode shape number 5 and 6 play an important role in horizontal displacement. The structure was satisfied with the Chinese design code with the total steel weight in this structure roof is 45kg/m^2.

IV. DESIGN optiEmization OF LAMELLAR-KIEWITT SINGLE-LAYER RETICULATED SHELL SUSPEND-DOME

The optimization was conducted on the basis of structure morphological parameter in order to utilize all material in any given elements to fully the extent of their stiffness and capacity. The parameters that commonly play a much important role in the steel roof structure such as its safety application, erection process, stiffness, rigidity, and especially the economy, should be wisely selected and optimized. The structural optimization under three main parameters such as rise-to-span ratios, strut-height, and single-layer reticulated shell types was randomly selected in this optimization.

1. Rise-to-span ratio

When the ratio of rise-to-span is larger, the reticulated shell behaves as arch alike and the vertical deformation can be increased with only less pretension used. However, a large value of roof height results in huge volume unused spaces under its shell, where it will cost much energy to cooling in summer and heating in cold weather for the entire gymnasium. Also defined in the building code of structure, the f/l value (f: roof height, l: span length) increases as the f increased that result in a larger value of the shape coefficient of wind load μ_s. The roof will be suffered from high wind pressure at windward, which causes the structure to be unstable or need to strengthen its dynamic resistance properties. On the other hand, a rigid shell resists the external load in form of a simply-supported beam when the ratio of rise-to-span is too small, and as a result of large deformation or higher pretension load required. As the consequence of rise-to-span selection can be greatly affected on structural performance and its working behavior. Roofing material will be a lot for big rise-span ration as the surface increased. Normally, the value of rise-to-span ratios will be set by the architectural concept model, but the collaboration between engineers and architects should play much more influent in the decision. Random rise-to-span values are chosen to be 1/5, 1/7, 1/10, 1/12, and 1/15 in the analysis of its effect on structural characteristic and economic.

The nodal displacement in Fig.9 indicates the overall vertical displacement of suspend-dome where large rise-span have less displacement than small rise-span, even though these values are all satisfied design code. For rise-to-span ratio 1/5 and 1/7, the initial pretension value is minimized in cable-strut system while the displacement is not significant, for example, the rigid member has almost no deflection at zero state, and single-layer shell play vital role in resisting external load. From ratio 1/10 and smaller, the deflection of suspend-dome roof was controlled mainly by the amount of pretensioned in cables, however, both single-layer and lower cable-strut system work harmoniously to decrease vertical displacement. The axial forces in cable-strut and single-layer members moment of the small rise-span ratio (1/10, 1/12 & 1/15) are found larger than in 1/5 and 1/7 ratios. These increasing stress and moment as the result of prestressing value is increased in order to achieve reasonable vertical displacement in smaller rise-span ratio. The graph of natural frequency of the first 15 mode is given in Fig.10, thoroughly describes that small rise-span is much better in resisting to the strong wind and earthquake. Thus, small rise-span ratio results in great integration of rigid shell with lower cable-strut by taking a fully advantages of members stiffness to decrease deflection, improve overall stiffness, and having higher dynamic resistance. The result of total steel consumption shows that rise-span 1/10 is the most economic.

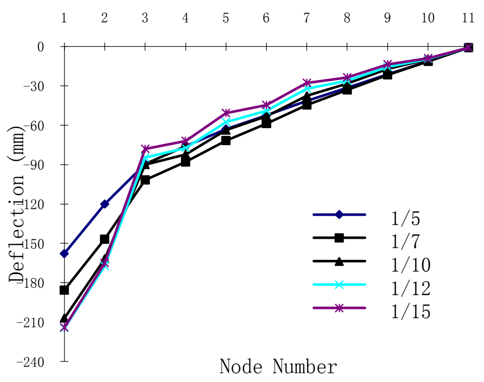


Fig. 9 Nodal displacement of various rise-span

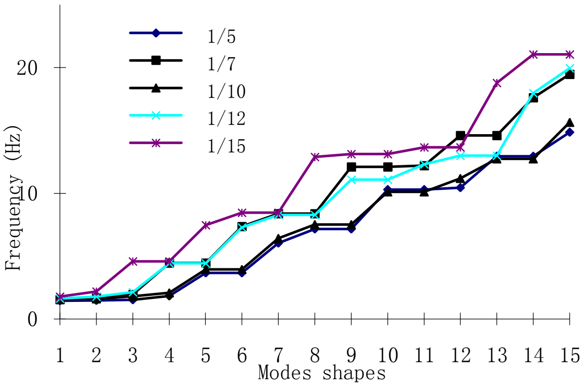


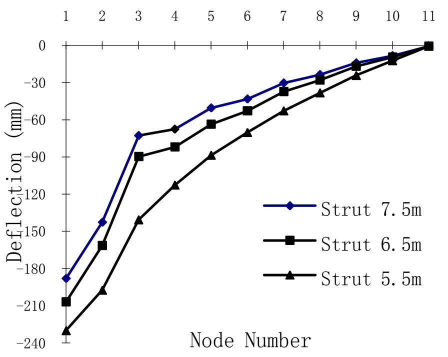
Fig.10 Natural frequency of the different rise-span

2. *Strut-height*

A strut behaves as the column support to resist vertical load from reticulated shell while its capacity to bearing the load completely depend on the applied pretension to the hoop cable and the inclined rod. The vertical axial force of the strut is defined by pretension in inclined rod and the angle θ of the inclined rods to the horizontal at its joints with the rigid shell. Increasing in angel θ, the strut length also increased longer, and the vertical axial force is larger that benefit in improving the vertical deformation. However, two things should be notice that when too long of the strut length will result in strut buckling issue, and a larger space under the roof is required. However, the higher strut can interfere the view angle of the audiences. The strut lengths were selected to be 5.5m, 6.5m, and 7.5m for outmost ring and relatively reduced 1m every inner ring.The nodal displacements in Fig.11, where shorter strut 5.5m is having large deflection, and strut 7.5m and 6.5m create similar vertical displacement. Large moment at central area and huge thrust force exists at the supports of single-layer reticulated shell happens in shorter struts suspend-dome. When angle θ is smaller, thrustforce (horizontal force) almost equal to applied tension F in inclined rod and the axial force in strut is decreased. Axial stresses are similar in all condition as the same value of pretension is applied to cable-strut system. However, longer strut resists less stress than shorter strut. The dynamic characteristics of all parameters strut height are similar for the first four mode shape (rotation of hoop cables), and the natural frequency of shortest strut increases higher than other two from the 5th modes shape, see Fig.12. Those structures are sensitive to torsion as the rotation along vertical axis. The amount of steel consumption in the project are almost the same for strut height of 6.5m and 7.5m, 45kg/m^2 and 45.5kg/m^2, respectively. In contrast, it is increased largely for strut 5.5m, as 72kg/m^2, this result from the increasing of single-layer member sections in order to achieve the satisfied deflection as mention in the code, while large prestressing force created less upward force along the strut axial.

3. *Single-layer Reticulated Shell Types*

The suspend-dome is sharing main rigid part as the single-layer reticulated shell, and those single-layer types play big role in the construction procedure and the amount of steel consumption in the whole project on the basis of joints types and method of construction. The convenient and flexible arrangement of the rigid members may result in saving times to assembly. Moreover, in previous section also indicated that single-layer shell together with cable-strut system have integrated and taken fully used of each member strength to increase the structure stiffness and result in less material usage. Hereby, a combination of Lamella with Kiewitt 8, original Kiewitt 8, and Lamella combined with ribbed dome were adopted in this section, see Fig.13.



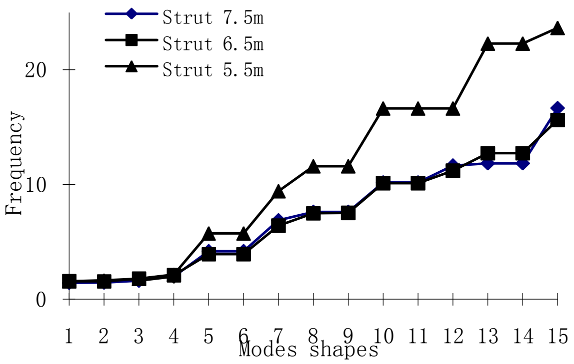
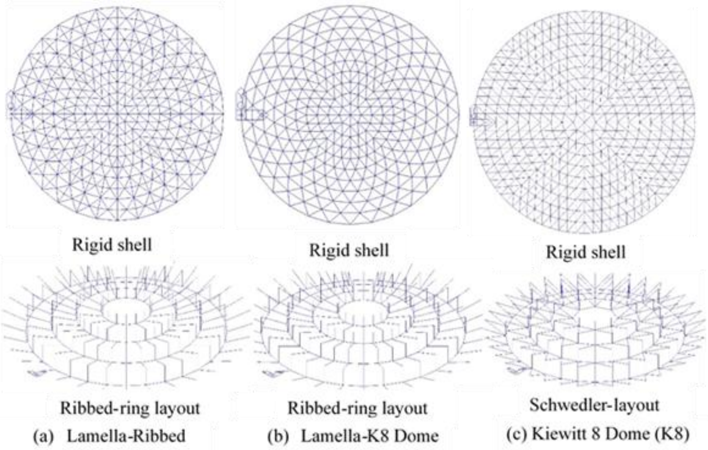
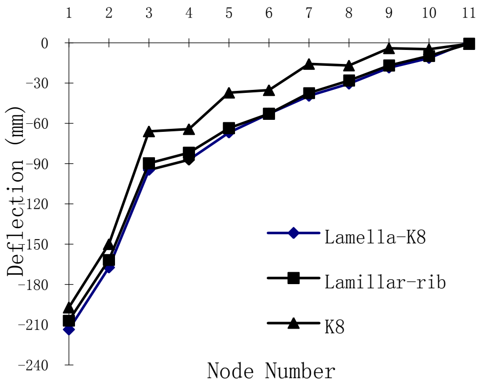


Fig. 11 Nodal displacement of various strut-height   Fig.12 Natural frequency of the different strut-height



(a) Lamella-Ribbed (b) Lamella-K8 Dome (c) Kiewitt 8 Dome (K8)

Fig. 13 Single-layer and their cable-strut layouts



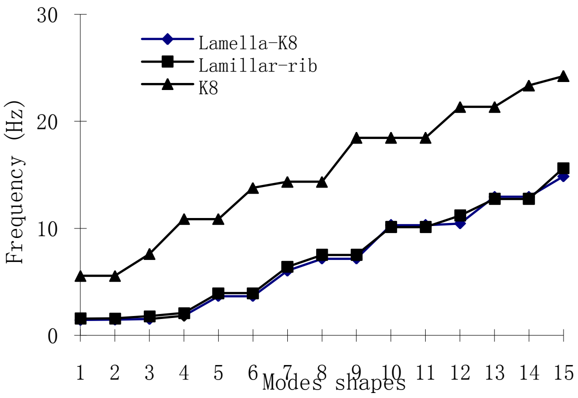


Fig. 14 Nodal displacement of various single-layerFig.15 Natural frequency of the different single-layer

The pretension force applied to the hoop cables and inclined rods was set to be equal, the nodal displacement of the single-reticulated shell become the crucial point to be discussed. The lowest deflection at node 1 of Kiewitt 8 (K8), Lamella-ribbed and Lamella-K8 is -197.2mm, -206.9mm, and -213.66mm, respectively (Fig.14). Their deflection graphs were not much different, even the deflection of K8 is the smallest. The axial strut stress of K8 is larger as Schwedler bi-direction layout was adopted in the lower cable-strut system, while others two reticulated shell are rib-ring.The graph of first 15 natural frequency modes shape of three different single-layer reticulated shells (Fig.15) has clearly shown about the vibration frequencies of Kiewitt 8, where the natural frequency is much greater than $5H_z$ while the frequency of Lamella types just less than $2H_z$ for the first mode shape. The two Lamella single-layer models are considerably having the same frequency for the first 15 modes shape, and their graph are the completely similar to K8 from 5^{th} mode shape. Thus, K8 natural frequency shows higher dynamic resistance, and rotation of hoop cables does not occur. On the basis of vibration of other two Lamella suspend-dome, the first four modes shape that does not appear in K8 suspend-dome, are the rotation of those 4 hoop cables of rib-ring layout. Improving the rotation stiffness of lower cable-strut system could result a better stiffness against dynamic load. Inclined strut or Schwedler layout might improve resistance to strong wind or earthquake action. The Lamella-rib is still the most economical structural types among others, as its steel consumption only 45kg/m^2, while Lamella-Kiewitt is 48.5kg/m^2 and 61.4kg/m^2 for Kiewitt 8 suspend dome.

V. CONCLUSION

In this paper, many aspects were raised up to provide a greater understanding of the system selection of large-span space structure and the analysis and design optimization of the suspend-dome structure of a 92m span. Several conclusions can be made from the structural system selection and analysis of the gymnasium roof:

- The Lamella-Kiewitt single-layer reticulated shell suspend-dome structural system was selected as the feasible system based on the advantage not only in geometry as it has great advantages in circular projection plan both structural arrangement and the procedure of pretension cable, but also the modern hybrid prestressing technology and industrialization of the single-layer reticulated shell.
- Rise-to-span ratio 1/7 to 1/10 is recommended as suspend-dome reaches its well-integrated performance between single-layer and the lower cable system, and advantages of hybrid structure concepts are obtained that result in lower direct index cost.
- Strut-height controls the efficiency of applied tension in the flexible member of the suspend-dome and minimizes the prestressed force as large prestressed will result in construction difficulties. The value of angle θ is recommended to be ranged from 17º~23º.
- The single-layer types do not have much difference in structure characteristic, but the arrangement of member affects interior view especially on the decisive selection of cable-strut layout. The ribbed-ring layout is more sensitive to strong wind and earthquake than Schwedler bi-directional layout.
- The total steel consumption of the optimized Lamella-Kiewitt single-layer reticulated shell suspend-dome structure with four circumferential ribs is about 45kg/m^2, which has a good economy.

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