International Journal of Engineering Innovation & Research
Volume 11, Issue 6, ISSN: 2277 – 5668

A Review on Developments in Application and Research of Suspen-Dome Structures

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Date of publication (dd/mm/yyyy): 26/12/2022

***Abstract* – A new-form of hybrid pre-stressed spatial structural system is called the suspen-dome structure. It consists of single-layer latticed shell structure and cable dome structure. The suspen-dome structure was reviewed along with the analysis of the background and mechanical principle, including many other parametric studies such as: form-finding analysis, static force and stability analysis, the dynamic behaviors and the earthquake resistant behavior, pre-stressing forces analysis and optimization design, and the research status of the design of the fir-resistant performance. Moreover, further research orientations of suspen dome structures are discussed and prospected.**

***Keywords* – Suspen-Dome, Applications, Research Progress, Static and dynamic analysis.**

I. Introduction

A popular solution for covering stadiums, sports halls and venue halls in wide area for nearly three decades, was the suspen-domes. The suspen-domes applications extend the span limits for grid dome systems because it can be easily constructed and maintained. The suspen-domes composed from a single layer dome and concentric tensegritic system. For the progress of society and the economy, the demand of the large span space structure has been increased. Because of the attractive mould, confirmed technique, and beneficial construction technique, the single-layer latticed shell used widely in small and medium sized span project. However, the structure is very responsive to the initial defect which makes its stability become the principal factor; the double layer shell overcomes the shortcomings of the weakness of the shell, but it possesses dense rod pieces. The dead load in large span will lead to larger tensile force in the surrounding ring beams and the usage of iron and project costs became higher.

II. Structural System of Suspen-Dome

A system of suspen-dome is consisting of two basic parts, the upper part and the lower part. For the upper part, consists of a single-layer of rigidly-jointed lattice dome. For the lower part, consists of an assembly of hoop cables, struts and diagonal cables. Hoop cables were creating a horizontal polygonal ring, where struts were connected to some nodes of the single-layer dome at the top end, and connect to hoop and diagonal cables at the bottom. For the diagonal cables, these cables connect the supports to the bottom ends of the outer strut and also the top and bottom ends of the struts as shown in Fig. 1.

III. Review Criteria

Suspen-dome was introduced by Kawaguchi [1], to solve the problems in the large span space structures, to overcome stability issues and reduce the weight of conventional spatial structures. The structure was a new kind of hybrid system which merged a tensegrity system (an assembly of cables and struts) with a single-layer lattice dome. In the system of suspen-dome, the overall stiffness of the single-layer lattice component of the dome was increased and at the same time, the excessive flexibility of the cable-strut component of the dome was decreased. The progress of this system was based on an effective integration of these two structural components, which make it more practical and economical long-span space structure.

The new system of Suspen-dome was invented by authors [1]-[3], as a dome named the Hikarigaoka dome. Suspen-dome structure of the railway has become a very popular because of its attractive mechanical properties, W. Kang et al.[4]. The suspen dome system was declared by Kitipornchai et al. [5] as is one of the most attractive space structures due to its excellent structural properties.

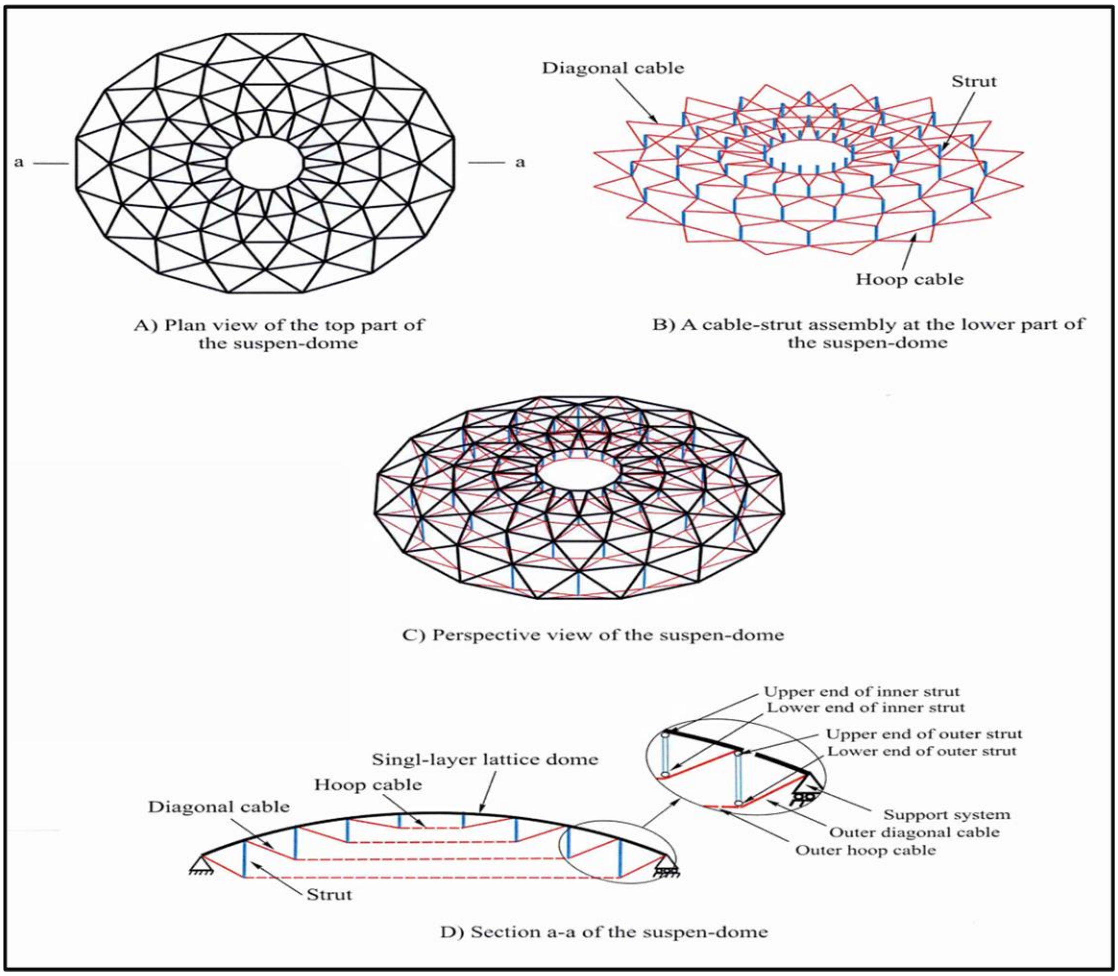

Fig. 1. Suspen-Dom System.

IV. Developments in Application and Research

Several key issues of Lamella suspen-dome structures addressed by Kitipornchai et al. [5] such as: the design of the cable pre-stress force method and the Lamella suspen-dome structure and the corresponding single layer Lamella dome comparison. An effective analysis method for the objective of studying the effects of cable pre-stress force and external load on the structural behavior of the suspen-dome system. A parametric study of structural characteristics and buckling capacity. The geometric imperfection effect, a symmetric loading, rise-to-span ratio and carried out the rigidity of connection on the buckling capacity of suspen-domes. The obtained results arise from the following:

- The bottom tensegrity system assists the dome structure increasing the buckling capacity, decreasing member stresses, and increasing stiffness.

- The geometric defect has a main role in the buckling of the suspen dome system. Where, 50% of the buckling capacity of a suspen-dome can be reduced by the geometric imperfection of system.
- The buckling was also affected by important factors like the connection rigidity and rise-to-span ratio. The pin-connected system has a lower buckling, especially for suspen-dome structures with small rise-to-span ratios.

The parameters influencing the free vibration behavior of suspen-dome structure were investigated by Cui et al. [6]. Basic on the time history analysis results: the boundary condition was the main influence factor of the seismic behavior. The results demonstrated that: when the boundary conditions were only fixed in vertical and tangential directions, the partial suspen-dome structures show good seismic behavior. While these conditions were the same, the suspen-dome structures have the similar seismic response in different level under horizontal and vertical earthquake action.

The Beijing Olympic Badminton Stadium studied by Ge et al. [7], the whole process of simulation calculation of the pre-stressed construction of the pre-stressed dome structure carried out to test the structural safety during the construction process and analyze the pre-stressed construction. In the process, it was assumed that, the structural shape change characteristics, internal force and joint displacement change law, and the pre-stress construction control parameters.

The background and the structural principles of suspen-dome system described by Sunyi et al. [8], by using the ANSYS software, the modal analysis and seismic analysis of the structure were carried out and obtained the dynamic features of the suspen-dome. The dynamic properties of suspen-dome were compared in un pre-stress force and pre-stress force to suspen-dome.

Three classification methods for the chord-supported dome structure system were proposed by chen et al. [9], According to the rigid and hinged connections of the upper chord members, they were divided, divided according to the type of the lower chord cable, and divided according to the upper single-layer reticulated shell. It was recommended to adopt the classification method according to the form of single-layer reticulated shell. Especially the joint-square type, the Kiewitt type and the joint- Kiewitt -type string dome structure according to the principle of convenient engineering application.

The suspend-dome with span of 98m, rise of 9.3m and rise-span ratio 1/10 in Badminton Gym for 2008 Olympic Games adopted by jiaqi et al. [10]. Force, displacement, Eigen-value buckling and nonlinear buckling to suspend-dome and single layer shell were conducted separately, the proof of selecting suspend-dome was provided. The axis force and joint displacement of upper dome as object function were developed respectively; the effective method of prestress level was researched. Studied the influence of initial geometrical defect on the integral stability and developed the method of applying initial geometrical defect.

At Tianjin Museum, frequencies of different construction stages were calculated by Zhihua et al. [11]. By ambient excitation method and hammer exciting method separately, dynamic tests at two construction stages were carried out. Test process and results were analyzed. From analysis, it was concluded that the suspen-dome structure has such properties as high basic frequency, closely distributed modes and sound integral structural performance. By contrast, the differences in the properties of suspen-dome structure at two stages were studied.

The analysis of construction process of a suspen-dome studied by jiaqi et al. [10], based on the non-linear fin-

-ite element theory, differentiating initial pre-stress state and zero state of suspen-dome. Ailin et al. indicated that: the construction of suspen-dome was a sequence process from zero state to initial state. To simulate and analyze the construction process, the release tension method can be used. According to analyze 2008 Olympic Games badminton gymnasium, the conditions of construction site were considered and tensile sequence of lower cable-strut was also decided, that all course analysis of the construction was simulated.

A Structural design of a practical spherical suspen-dome with the diameter of 122m carried out by Zhang et al. [12], in China Construction Design International (CCDI) in 2006. He investigated the self-internal-force mode and the pre-stress level ratio between three ring cables to calculate the pre-stress in the cable. To confirm the pre-stress efficiency, linear static analyses were then carried out. Also, the linear elastic buckling and the geometrically nonlinear stability analysis were presented. The obtained results arise the following:

- The deformation and the internal force of the suspen dome structure have been influenced by pre-stress induced in the cable and the strut.
- Also, the imperfections and live load distribution patterns have much influence on the buckling strength and the mode.
- For large-span structure, design limitations should be based on the buckling strength of the structure.

The badminton arena was studied by Ailin et al. [13], a 93m span of the suspend-dome of the badminton arena for 2008 Olympic Games, and the average steel cost is optimized down to about 60 kg/m2. To monitor the force of the members and tension of cables, the vibratory strain gauge and total station instruments were used. During construction, displacements of joints were monitored and the data offers that, the force, displacement and cable tension were all within reasonable range.

A suspen-dome system in roof of Lianyungang gymnasium introduced by Honglei et al. [14], including the characteristic of the roof structure system, loads calculation, the principle of pre-stress value, static performance analysis and elasto-plastic analysis of the connection joint of cable and strut. At the end, by using elasto-plastic finite element method, the researches of structural ultimate bearing capacity have been carried out effectively, and the structural safety has been discussed.

An optimization for hoop cable pre-stressing using first-order method by ANSYS software of suspen dome with stacked arch (Chiping gymnasium) was carried out by Chen et al. [15]. The following conclusions could be obtained:

- The structure of SSA is rational, and has some strength reservation in some way;
- In summer, the non-uniformity of temperature distribution of SSA, and the value of temperature is also high under solar radiation;
- Considering the stress in the element induced by temperature.

A design procedure for a proposed sport center located at Jinan city was created by Zhang et al. [16] since no provisional design codes were provided for the suspen-dome system. To analyze the structure using the ANSYS software, taking into consideration the self-internal-force and the pre-stress ratio among the three ring cables in order to verify the pre-stress in the cable. Also, parameters such as; the buckling, static, geometrical nonlinear b-
-uckling, modal, time history, response spectrum, wind induced effect and construction cable failure and node d-

-esign were all analyzed.

Zhang et al. [17] they studied the basic conception of temperature distribution and thinks about the variation of pre-stressing cable force due to temperature variation; integral stability analysis of suspen-dome structure due to the temperature variation by structure buckling analysis by using ANSYS software in the badminton gymnasium of 2008 Olympic Games. Results offered that, the stability of suspend-dome structure was well under normal temperature; with increasing in temperature, the stability coefficient increases continuously. The conclusion was: the pre-stress construction of the suspend-dome structure was suitable to be finished in summer.

The parametric optimization design of the suspen-dome structure was analyzed by Liu Shutang [18] with structure weight as the object function in consideration of the member's stability, strength, stiffness and structural displacement constraints. The lightest structural weight achieves its minimum values when the depth-span ratio is from 0.13 to 0.15. When the depth-span ratio is smaller than 0.13, the rise-depth ratio has larger effect on the lightest structural weight under a definite depth-span ratio. With the increase of the depth-span ratio the latitudinal cable prestress ratio increases linearly, and the outer latitudinal cable prestress decreases linearly. Under a definite depth-span ratio the larger rise-depth ratio results in the larger latitudinal cable prestress ratio and outer latitudinal cable prestress. The fundamental structural period obtains its minimum value when the depth-span ratio is from 0.16 to 0.17. The larger rise-depth ratio results in the smaller fundamental structural period. With the increase of the depth-span ratio the strut section standard increases obviously, and the outer latitudinal cable section standard decreases obviously.

The worst distribution and magnitude of initial geometrical imperfection during stability calculation is studied by Jiamin Guo [19]. 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.

A practical suspen-dome project, Changzhou Gym roof (as an example) was adopted by Chen et al. [20], and its transient analysis based on the multi-support excitations of the earthquake wave was carried out. With comparing the single support excitation, value and position of the maximum stress under multi-support excitations both change and the number of elements with clear changes was large and more than 70% of the total. The result shows that the earthquake wave influence effect on the structure system was negative and cannot be ignored.

A new type of multi-node sliding cable element formulated by Chen et al. [21], for cable structures analysis with sliding cables. The element has random number of sliding nodes and satisfies uniform strain assumption. The multi-node sliding cable element implemented in ABAQUS software as a user defined element and applied in the static and nonlinear stability analysis of a Suspen-Dome structure under the action of both symmetric and asymmetric loads after the derivation of the tangent stiffness matrix. The conclusions as following:

- The rationality and effectiveness of the nonlinear multi-node sliding cable element were verified for both sliding and non-sliding situations.
- With the sliding of the latitudinal cables, uniform axial force distribution can be achieved for the tensegritic system of the suspen-dome, which was helpful for improving the material efficiency of the cables and preventing the cables from sagging under asymmetric loads.

Huijuan et al. [22], studied the actual suspen-dome projects, extracted the key construction parameters for them and tensioning mechanism of hoop cables. Then according to the tensioning mechanism and the key construction parameters, a numerical model and an algorithm for the whole process of tensioning were proposed. Moreover, a case study was addressed to approve the effectiveness.

The statically behavior of kiewitte suspen-dome was studied by Li et al. [23], using finite element method, and ADINA software application to implement the analysis. A certain suspen-dome was studied; the internal forces, deformation and support constrained forces of the structure were obtained. Also, the influences of parameters including prestress, stay bar length, cross sectional area and rise-to span ratio were discussed. The results display that, the increase of vertical stay bar length and prestress can improve the suspen-dome stiffness; cross-sectional area has nearly no impact on the static behavior, and the rise-span ratio was the most sensitive parameter.

Liu et al. [24] they studied the friction effect between the hoop cables and cable-strut joints on the pre-stressing construction of suspen-dome structures, and presented a simplified method based on frozen-heated theory and large curvature assumption. This method used to simulate the pre-stressing construction of suspen-dome, only a few program codes were needed to write by APDL language in ANSYS software. It was very convenient. The results were showed that:

- The pre-stressing construction process can be effectively simulated.
- By both non-curvature assumption and curvature assumption for suspen-dome structures, the sliding friction can be effectively calculated.
- The sliding friction makes a significant effect on the pre-stressing construction.
- For future design of suspen-dome, the cable-strut joint with small friction coefficient was suggested.

A new type of continuous cable joint on a suspen-dome with a stacked arch was investigated by Liu et al. [25]. The cable joint was in two states, locked state and unlocked state. It was concluded that:

- When the continuous cable joint was locked, the critical load was higher than that when the of continuous cable joint was unlocked.
- The adjacent members will share some displacement and member stress, if the continuous cable joint was locked, and if local nodal displacement or member stress was extreme large.
- If the continuous cable joint was unlocked, the adjacent members cannot share some displacement and member stress effectively, if local nodal displacement or member stress was extreme large.
- The stability under condition that the continuous cable joint was unlocked compared with locked, the stability behavior was better under condition that the continuous cable joint was locked.

The effect of pre-stressing loss and sliding friction during construction on the structural behavior of suspen-dome structures were studied by Hongbo et al. [26]. The conclusions were obtained from results:

- The sliding friction during pre-stressing construction induced the pre-stressing loss has a remarkable effect on the mechanical behavior of suspen-dome under dead load and live load.
- Under asymmetrical load, the structural behavior of suspen-dome structure was different when the sliding friction coefficient between hoop cable and cable-strut joint was changing. When the sliding friction coefficient was large enough to make the hoop cable not sliding around joint, the structural behavior was the best case.
- The construction process of suspen-dome structures has a remarkable effect on its structural behavior during service time under dead load and live load.

The Construction sequence simulation analysis of a practical suspen-dome of Jinan Olympic Center was discussed by Zhiqiang et al. [27]. Using the random imperfection modal method to simulate the construction error of the structure. The integral structure model including the concrete supporting system and the effect of the temperature variation on the suspen-dome were used in analysis. The following results obtained as following:

- Effects of different supporting conditions on the upper single layer latticed shell of the suspen-dome were not significant.
- Under an ultimate magnitude for its significant effect on suspen-dome, nodal spatial position errors should be restricted.
- It is obtained little effects of construction errors on the mean axial internal-force among each group of cable-bar elements, while a great effect on the standard deviation of the axial force was obtained. And the effect of temperature variation was just on the contrary.

A nonlinear numerical analysis method based on the time integral effect for a suspen-dome structure considering the temperature field distribution, displacement and stress were established by Zong et al. [28]. The results obtained as following:

- As a temperature rising, the strength and elastic modulus of steel decrease. The large loss of pre-stress under high temperature as well as thermal expansion causes the reduction of stiffness of structure components, which results in structural deformation increase.
- The main characteristics of deformation of suspen-dome structure were arch. The deformation increases with temperature rising, the deformation changes faster under fire and the central deformation is the maximum, which reflect the hoop function of the concrete beam under the fire and indicate high security of the structure design.

The variation of thermal behavior over time under summer solar radiation of the SDSA (Suspen-Dome with Stacked Arches) structure as well as the effect of cable sliding friction and healing temperature on the non-uniform thermal behavior was studied by Liu et al. [29]. The analysis allows the following:

- A significant effect of solar radiation on the thermal behavior of the SDSA structure, and the operation or not of the indoor air conditioning system has only a slight effect on the thermal behavior of the SDSA struc-

-tures.

- The distribution of its force in each hoop cable when the hoop cable cannot slide around the cable–strut joint was most uneven under non uniform thermal loading, especially for the inner hoop cables, and the variation was up to 190% about the mean.

Wang et al. [30] established the initial state of construction process according to practical construction sequence to accurately simulate pre-stressed construction process of large-span suspen-dome. And the construction mechanical analysis for pre-stressed construction process was especially studied. Yangquan et al. summarized the features of prestressed construction process of large-span suspen-dome, and the insufficiencies of the application of state variable superposition method; the method of back analysis, birth and death element method were also analyzed. The conclusion was, based on the equivalent pre-tension using forward algorithm for prestressed construction process, it can be accurately tracked for the structure state of each construction phase, and the nonlinear contact of strut and rigid framework, also, structural geometric nonlinearity can be comprehensively considered. The pre-stressing force deviation induced by sliding friction and temperature between the hoop cables and cable strut joints during the pre-stressing construction of a suspen-dome structure were investigated by Hongbo et al. [31]. Five advanced pre-stressing construction measurements were presented to reduce pre-stressing deviation. Increasing the pre-stressing joint, over pre-stressing the construction, adoption of rolling cable strut joints, modification of pre-stressing construction control values that considered temperature change and selection of the hottest time for pre-stressing construction measurements were included. It was concluded that: the experimental and numerical results from the construction measures could effectively reduce the pre-stressing deviation.

A novel form analysis method considering pretension process for suspen-dome structures was modeled by Zhen et al. [32]. Using a combining inverse form-iteration and sequential pretension-simulation, the nodal coordinates in zero state and initial strains for actively tensioned cables can be accurately solved through the proposed method. Since the influence of pretension process was included, the results form analysis can be automatically output the tensioning control force scheme for active cables and forces in passive cables as well as nodal displacement in each pretension state. The results from the numerical example showed that both the error of nodal coordinates and cable forces can stably converge to the set tolerance. The form analysis results can accurately achieve the expected initial state. The influence of member geometric imperfection on nonlinear buckling and seismic performance of suspen-dome structures were studied by Zhou et al. [33]. Supposing the initial curvature of members as half-wave sinusoids, a stiffness equation of imperfect truss elements was developed for struts. While that of imperfect beam elements was derived for reticulated shell members. As the example of testing, an ellipsoidal suspen-dome employed as the roof structure of Changzhou gymnasium was taken. The proposed imperfect elements were employed in the nonlinear buckling and seismic analyses of the ellipsoidal suspen-dome structure were taken in consideration of geometrical nonlinearity. The results present that the imperfection value has relatively great influence on the structural stiffness. The critical load decreases in a basically linear way by increasing member imperfection. For nonlinear seismic analysis, when imperfection was included, the initial state responses were different, namely, the seismic displacement increases while the stress in rods and cables decreases.

The rolling cable-strut joints in the suspen-dome of Chiping Stadium in Shandong Province to reduce the pre-stress loss in the pre-stressing process were adopted by Chen et al. [34]. Using a 1:10 scaled-down model of Chiping Stadium in the tension test and the loading tests to study the mechanical properties of the suspen-dome with rolling cable-strut joints installed. Also, a comparative experiment on static properties of the suspen-dome and the single-layer reticulated shell was conducted for the first time in China. The results were obtained as following.

- Considered, the test devices and surrounding environment in the design of the test model, a laser tracker could be applied in the test when the deflection was difficult to measure.
- The most significant influence on the suspen-dome was the pretension of the outmost circle (i.e., the 1st circle) of the hoop cable. After the second step of stretching the 1st circle of the hoop cable was completed, internal forces of the 2nd, the 3rd and the 4th circles of hoop cables increase 44.51% ~ 65.32%, 14.46% ~ 22.02% and 2.86% ~ 10.97% respectively. Also, internal forces of the hoop cables of which the prestressing process has already finished would increase due to the pretension of subsequent hoop cables, and the pretension of adjacent circles of cables would have the greatest influence on each other.
- The trend of changes of internal forces of radial tension members was like that of hoop Cables, since internal forces of radial tension bars were generated due to the pre-tension of hoop cables. However, the stress distribution of radial tension bars was uneven due to the friction loss between hoop cables and joints.

Two tests on a 10:1 scaled-down suspen-dome model were conducted by Wang et al. [35], to investigate the dynamic response and mechanical changes. To realize the sudden failure of cable, a special rupture device was invented. By using a high-speed video camera, the internal force variations of different members were measured and dynamic member-moving procedures around the break region were captured. Near the breaking point, the internal forces of the members experienced large vibrations at the breaking moment.

Liu et al. [36] proposed a modified double-control form-finding (MDFF) method with consideration of the construction process and the friction of cable–strut joints based on a transient structural model of a suspen-dome. The incremental equilibrium equation was built to include geometric nonlinearity according to the total Lagrangian increment formulation. First, the nodal displacement, displacement condition and the tangent stiffness matrix were built, and the finite element equations were calculated based on the existing members using the geometric nonlinear finite element method (FEM). Then, the nodal displacement, displacement condition and the tangent stiffness matrix were modified based on the newly added members and the friction of the cable–strut joints in present stage. The results of a numerical test on a suspen-dome, the proposed MDFF was found to be more accurate than the traditional double-control form finding method (DFF).

Number of suspen-dome structures was built by Sun et al. [37], but there were some difficulties in using experimental data to obtain good modal parameters, especially modal of damping. An ANSYS software numerical simulation of the 35.4m span of suspen-dome is presented. In the first, obtained the natural vibration characteristics of suspen-dome and dynamic response under some random forces. The results of the numerical simulation established that 60 modes were sufficient for a reasonable dynamic model. This model was used to represent the suspen-dome dynamic behavior, and OKID was then used to try to identify a model from simulated data. The results showed that, it can be a very efficient tool for the identification of models of suspen-dome dynamics.

A preliminary assessment of the dynamic behavior of carbon fiber reinforced polymer cable in a suspen dome in comparison with that of the steel counterpart were studied by Olofin et al. [38], using a small model of 4 m span and 0.4 m rise. For the structural simulation, using the ANSYS software. The results present that the carbon fiber reinforced polymer cable gives a reliable assessment as the steel counterpart. For the natural frequencies, the natural frequencies of CFRP cables were higher than those of steel cables due to the CFRP cables' high stiffness-to-weight ratio and less curvature under gravity loads.

Zhang et al. [39] proposed an improved rigid cable method, for considering the losses of pre-stress in suspen-dome structure after pre-stress optimization using rigid cable method. To compensate the loss of pre-stress, the temperature stress was applied to corresponding element, and the relationship between temperature and pre-stress loss was deduced. Results showed that the improved rigid cable method was effective and applicable.

Zhao et al. [40] studied a novel numerical method based on general finite element software. Using the nonlinear spring element to model the influence of friction. First, the reliability and applicability of the method was validated. After that, the numerical model of suspen-dome was established by incorporating the nonlinear spring element. The results of influence of friction on the buckling capacity of the suspen dome structures were indicated that the buckling capacity increased with the increase in the friction coefficient. The buckling capacity can be maximized in the non-sliding condition. Results shows that, the numerical model that considered friction can be established efficiently in the overall structure model based on general finite element software and can thus be adopted for dynamic analysis. The feasibility of using CFRP cable as tension cables in suspen domes investigated by IfeOlorun et al. [41] in order to acquire more knowledge about its behavioral patterns. This paper gives preliminary findings of a successfully designed and constructed suspen dome prototype which comprehensively deepens the understanding of CFRP cable performance as a cable-strut system in a suspen dome. Results show that with its high stiffness, low weight and high strength, CFRP has proven to be a technically efficient and adequately strengthening material for structurally improving the adequacy of a suspen dome.

V. Conclusion

At present, researches on the suspen-dome structure are not thorough, the upper researches work in the static and dynamic performance of the suspen-dome structure, construction forming, structural optimization design, and stability. Some of the problems still lag behind the needs of engineering practice. For study on the suspen-dome structural system, both theoretically and practically will be great significant. Basically, on the current situation of research, there are mainly problems like:

a. A few and limited researches on some new forms of suspen-dome such as the mixed-layer suspen-dome structure, FRP cable suspen-dome structure are quiet. To meet the needs of new development, it is necessary to come up with more new forms of suspen-dome structures.

b. It is more difficult and few studies on the structural shape optimization, topology optimization and layout optimization.

c. Super long span suspen-dome structures are still having a little theoretical research on. When span increasing, the stability and dynamic characteristics of the structure will be more complex.

d. A further study on the effects of both geometric imperfections and physical imperfections (including mater-

-ial damage, crack defect etc.) on the structural stability will be a problem worthy.

e. Consistent input method is usually adopted in seismic response analysis in dynamic performance. Otherwise, the long span structures or super long span structures should adopt multi-point or multidimensional and multi-point method based on non-uniform excitation to seismic response analysis considering the time-lag effect in the propagation process of seismic vibration. Also, there are few studies on dynamic stability of the suspen-dome structures.

f. At the starting stage, the theoretical research of suspen-dome structure is still. And the problem of how to effectively take into account the reliability change of structure in the construction phase and the effects of the construction process on the reliability of the final forming structure is virtually worth researching deeply.

g. Some unexpected factors or errors of workers have effects on, such as geometrical defects of structural members, physical defects, joint localization, welding quality, boundary condition, operating methods and technical level. Also, errors caused by these factors are random and it is difficult to conduct quantitative analysis.

A variety of cable force test methods were found, but the cable force test technology is still a difficulty. So, the reliability of data in the testing process and improve the accuracy of test results are problems worthy of further study.

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