Design Optimization and Structural Property Study on Suspendome with Stacked Arch in Chiping Gymnasium

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Abstract

A new structural example, suspendome with stacked arch is accepted in Chiping gymnasium. In order to reduce the cost and to obtain a rational structure, an optimization for hoop cable pre-stressing is carried out firstly using first-order method by ANSYS software. Based on the characteristic of Chiping gymnasium, the temperature distribution of it is analyzed, and the temperature value for each element is obtained. Then for understanding the structural property of this new structure well, the static behavior is analyzed by building a three-dimensional FE model in ANSYS. Based on the research in this paper, it is concluded that a considerable stress could be induced by temperature load for Chiping gymnasium.

Keywords: suspendome, arch, optimization, temperature load, structural property

1. Introduction

The architectural shape of Chiping gymnasium consists of both spatial arches and spherical shell, and the arches above the spherical shell are connected to spherical shell by struts, as shown in Fig. 1. Suspendome structure is accepted for spherical shell through preliminary structural optimization[1,2]. Including the arches above the suspendome, a new spatial structure example is formed, that is suspendome with stacked arch[3] (hereinafter referred to as SSA in this paper), as shown in Fig. 2.

As shown in Fig. 1 and Fig. 2, SSA in Chiping gymnasium consists of indoor suspendome (with span of 108m) and outdoor arches (with span of 190m). Mesh type of single-layer reticulated dome consists of both keweit type (denoted by black color in Fig. 3) and lamella type (denoted by red color in Fig. 3). The cable-strut system of suspendome is composed of seven loops as shown in Fig. 4. Two rings of bearing are set in this structure , and one of them locates in the intersection boundary between the keweit mesh type and lamella mesh type , and the other in the outer ring of lamella mesh type. The radial direction of bearing is free, and vertical direction is fixed, and the hoop direction is elastic restraint with stiffness coefficient of $2800\,kN/m$. As shown in Fig. 1, the roof surface consists of two types of material, lightweight steel roofing and glass roofing.

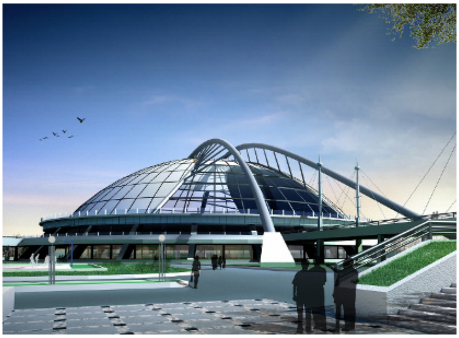

Fig. 1 profile picture of Chiping gymnasium

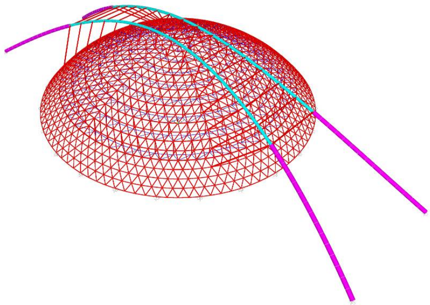

Fig. 2 arrangement plan of Suspendome with Stacked Arch

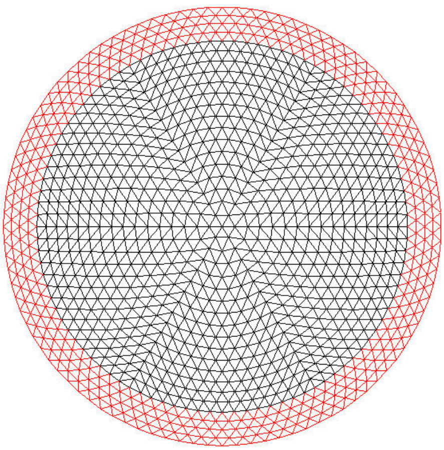

Fig. 3 mesh type of dome

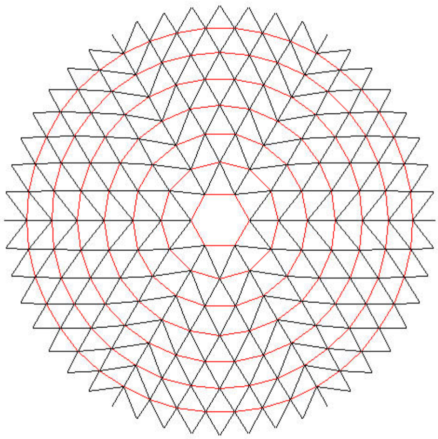

Fig. 4 arrangement of radial cable and loop cable

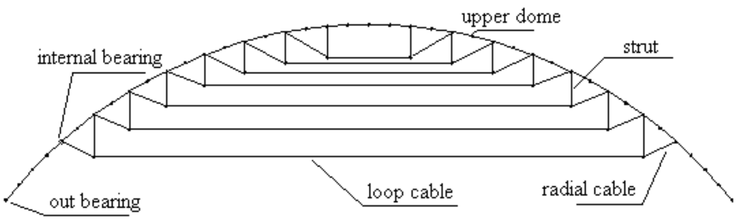

Fig. 5 sectional view of suspendome in Chiping gymnasium

In order to obtain a rational structure, an optimization analysis of hoop cable pre-stressing in suspendome is carried out in this paper firstly. Then based on the characteristic of Chiping gymnasium, the temperature distribution of it is analyzed. For understanding the structural property under various load cases, load effects under fifteen typical load cases are analyzed in this paper.

2. Optimization for pre-stressing of hoop cable

The key mechanical principle of suspendome structure is to transform the pre-stress in the hoop cable to horizontal force and vertical force at upper dome joints through radial cable and struts of cable-strut system, so the internal force of element and thrust force of bearing in upper dome of suspendome induced by vertical load will be counteracted effectively. There is a group of pre-stressing for all hoop cables, which can make the internal force and thrust foece least. This group of pre-stressing can be obtained by optimization analysis.

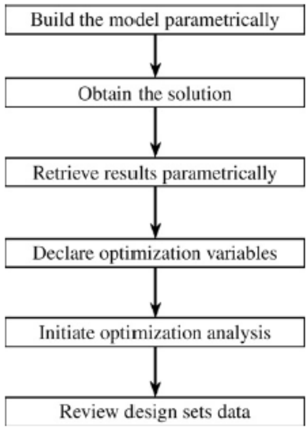

Fig.6 general process for design ptimizition in ANSYS

At present, there are two main methods for structural optimization, one is genetic algorithm, and the other is using ANSYS software. For the former, a lot of source programe must be designed if used, but the latter is not. So an optimization is conducted by using ANSYS software in this paper[4,5]. The general process for design optimization in ANSYS is shown in Fig.6, in which the optimization variables are the followings:

Design variable (DV): DV is the independent variable. Here, the DV is the pre-stressing of hoops cables.

State variable (SV): SV is the usual response quantity that constrain the design. Here, the SV is the maximum nodal displacement(less than 30mm used in this paper).

Objective Function: The objective function is the quantity trying to minimize or maximize. and in this design optimization it is the absolute value of the maximum stress of upper dome elements under dead load and half of live load.

An FE model for SSA (Fig. 4) is built firstly in the optimization anlysis using an advanced parametric design language (APDL) in ANSYS. In the model, the element of single-layer reticulated dome and spacial arches are simulated using BEAM188 element, the struts and radial direction element in cable-strut system using LINK8 element, the hoop cables using LINK10 element. Both of the material nonlinearities and geometrical nonlinearities can be considered in this FE model. Thus, this FE model is capable of simulating the full range behavior of SSA during the stretching phase, serviceability phase and ultimate load carrying phase.

Based on the optimization method presented above, the best pre-stressing for hoop cables are obtained. Under the optimal pre-stressing, dead load and half of live load, the maximum stress of upper dome elements is156Mpa, and the force of radial cables in seven loops is listed in table1.

Table 1 best pre-stressing in loop cables under dead load and half of live load

Cable NUM	HC1	HC2	HC3	HC4	HC5	HC6	HC7
Prestress value(KN)	127	420	390	530	810	1242	2060

3. Static behavior analysis

3.1 Load value

According to the load code for the design of building structures (GB50009-2001) [5,7], the normal value of permanent load, live load and wind load in Chiping gymnasium can be calculated easily and listed in table 2. For the temperature load, the distribution of it on roof element is very non-uniform due to the solar radiation. Based on the shape and structure of gymnasium, it is divided into three temperture fields. The first is outdoor arches, the second is field under glass roof, and the third is field under lightweigh steel roof. Considering the effect of solar radiation and the monitoring data in Chiping above, the temperature of these three fields accepted in this paper is listed in table 3.

Table 2 load of Chiping gymnasium

	loaction	Load value
Dead load (DL)	lightweight steel roofing	0.4 kN/m2
	glass roofing	0.7 kN/m2
	Pathway for maintenance	1.3kN/m2
Live load (LL)	Both lightweight steel and glass roofing	0.5kN/m2
Wind load(WL)	Reference wind pressure is $0.5kN/m^2$;the type of surface roughness is C 。wind load shape coefficient is calculated according to spherical shell; wind vibration coefficient is 1.2.	

3.2 Results analysis

According to the load code for the design of building structures (GB50009-2001), more than one hundred load cases are analyzed for the Chiping gymnasium in the design phase. The results of fifteen typical load cases selected from those load cases are listed in table 4.

Table 3 temperature load in Chiping gymnasium structure

Positive thermal load (TPL)	Healing temperature ^oC	Temperature of outdoor arch ^oC	Temperature of element under glass roof ^oC	Temperature of element under lightweigh steel roof ^oC
	-1	61	52	41
Negative thermal load (TNL)	Healing temperature ^oC	Temperature of outdoor arch ^oC	Temperature of element under glass roof ^oC	Temperature of element under lightweigh steel roof ^oC
	12	40	40	40

Table 4 typical load case combination in desgin of Chiping gymnasium

NUM	Load case description
1	1.0*DL
2	1.2*DL+1.4*LL
3	1.35*DL+0.98*LL
4	1.0*DL+1.4*WL
5	1.2*DL+1.4*WL
6	1.2*DL+1.4*LL+1.4*0.6*WL
7	1.2*DL+1.4*0.7*LL+1.4*WL
8	1.2DL+1.4*TPL
9	1.2DL+1.4*TNL
10	1.2DL+1.4LL+1.4*0.6*WL+1.4*0.7*TPL
11	1.2DL+1.4LL+1.4*0.6*WL+1.4*0.7*TNL
12	1.2*DL+1.4*0.7*LL+1.4*WL+1.4*0.7*TPL
13	1.2*DL+1.4*0.7*LL+1.4*WL+1.4*0.7*TNL
14	1.2*DL+1.7*0.7*LL+1.4*0.6*WL+1.4*TPL
15	1.2*DL+1.7*0.7*LL+1.4*0.6*W+1.4*TNL

According to the code for design of steel structures(GB50017-2003)[6], stress rations under fifteen typical load cases are calculated using ANSYS software. The statistics data of all stress rations is listed in table 5. And in table 5, the value is the rations of the number of element of which stress rations is among the corresponding intervals to the sum number of element of SSA. From the table 5, the following conclusions are obtained:

1) For fifteen typical load cases, the stress ration of most element in SSA is below 0.7, so the structure is rational, and has some strength reservation in some way;

2) Stress ration of the load cases including temperature load, especially of load case 14, is lager than that not including thermal load, so for Chiping gymnasium structure, the stress in the element induced by temperature is considerable.

Table 4 stress ration under fifteen typical load case

Case NUM	Statistics of stress rations in each intervals						
	0-0.1	0.1-0.3	0.3-0.5	0.5-0.7	0.7-0.8	0.8-0.9	>0.9
1	0.275729	0.507741	0.192395	0.024135	0	0	0
2	0.195355	0.535747	0.225638	0.041439	0.001821	0	0
3	0.193078	0.52459	0.235883	0.041894	0.003643	0.000911	0
4	0.255237	0.530738	0.137978	0.052368	0.016393	0.007286	0
5	0.272769	0.533015	0.137067	0.049408	0.007741	0	0
6	0.288934	0.523452	0.164845	0.022769	0	0	0
7	0.285064	0.536658	0.14276	0.035519	0	0	0
8	0.257058	0.401184	0.184426	0.103597	0.029144	0.021858	0.002732
9	0.186931	0.356557	0.295993	0.112933	0.030282	0.01275	0.004554
10	0.321038	0.422814	0.179189	0.07377	0.003188	0	0
11	0.204918	0.428051	0.266849	0.091985	0.007286	0.000911	0
12	0.213115	0.515483	0.177596	0.070583	0.016849	0.006375	0
13	0.21653	0.461293	0.229736	0.085155	0.006375	0.000911	0
14	0.220401	0.424408	0.196949	0.099954	0.029599	0.023224	0.005464
15	0.200364	0.385929	0.260929	0.11225	0.025956	0.010474	0.004098

The reason why thermal stress is considerable could be understood by analysis of the characteristics of SSA. The reasons can be concluded of the following:

1) The entire arches are located outdoor, so their temperature is very high under solar radiation in summer;

2) The solar radiation can penetrate the glass roof , so the temperature of elements under glass roof is also very high in summer;

3) The thermal displacement between outdoor arches and indoor suspendome is incoordination.

Due to the three reasons above, the stress of element in SSA is very high. So there is much work needing to reduce the effect of thermal load, such as painting light color on surface of arch elements for reducing the absorption quantity of solar radiation , adjusting the cross section of arch for making the dispalcement between outdoor arch and indoor suspendome coordination, using special glass for reducing the permeation quantity of solar radiation and so on.

4. Conclusions

Based on the architectural shape of Chiping gymnasium, a new spatial structural system, suspendome with stacked arch (SSA), is presented in this paper. In order to obtain a rational structure design, a best group of hoop cable pre-stressing is found by using first order method in ANSYS. Through load analysis and static analysis, the following conclusions could be obtained:

1) The structure of SSA is rational, and has some strength reservation in some way;

2) The temperature distribution of SSA is very non-uniform, and the temperature value is also high under solar radiation in summer;

3) The stress in the element induced by temperature is considerable.

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