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DEVELOPMENT AND APPLICATION OF GLOBAL-PROCESS TENSION ANALYSIS SOFTWARE FOR SUSPEND-DOME BASED ON ANSYS

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Suspend-dome includes a single-layer latticed shell and the bottom tensegrity system. The overall stress state is closely related to the construction tension process. In order to provide guidance for safe construction of suspend-dome and trouble-free operation, an iterative method to determine initial strains of the bottom tensegrity system under zero state was proposed, and software for global-process tension analysis was developed based on ANSYS. A transform interface module was developed for rapid ANSYS parametric modeling. The optimization was conducted to achieve optimal prestress. A computational module was developed for the form-finding, force-finding, and construction tension analysis. The construction process of a suspend-dome with a span of 106 m was simulated by using the construction simulation method. It was shown that the iterative tension analysis method provided accurate and reliable simulations, which could be further used to determine the prestress and form of suspend-dome. The presuppositions and obtained computation sequences of the construction simulation method agree well with the practical construction process. This construction simulation method can be utilized for construction simulation.

Keywords: Prestress, Optimization, Construction simulation, Form-finding, APDL.

1 INTRODUCTION

Suspend-dome structure is a new type of prestressed long-span spatial structure, which integrates the advantages of cable dome and latticed shell in view of the tensegrity system concept. The increasing applications of suspend-dome have been witnessed in recent years with various forms, including a 35*m* span light dome in Japan, the Yueqing Sports Center Gymnasium with a 148 m span, the Wuhan Sports Center Gymnasium with an ellipsoid upper latticed shell, and the Anhui University Gymnasium with a common hexagon shape. The development and extension of the concept of suspend-dome call for higher requirements for design and construction (Chen 2011).

The upper part of the suspend-dome system is a statically indeterminate rigid structure, while the lower part can be regarded as a flexible tensioning structure. The shape of the structural form is dependent on the distribution of prestress and the method of construction tension. In the current design codes, the target prestress is mostly determined by the trial method. Either the cooling method or the target force method is adopted in the construction tension analysis. The cooling method cannot avoid the loss of prestress caused by structural deformation. The target force method can only be used to simulate a simple construction process with difficulty in convergence (Wang and Ni 2015). To improve the efficiency and accuracy of analysis, a global-process tension analysis software for suspend-dome structures was developed by using the software package ANSYS and the excellent parametric function of APDL (ANSYS Parametric Design Language).

2 DEVELOPMENT ROUTE AND IMPLEMENTATION

The overall software flowchart is shown in Figure 1. It can be seen that the software has been divided into four modules: Transform interface, Prestress optimization analysis, Construction pretension analysis, and Post-processing.

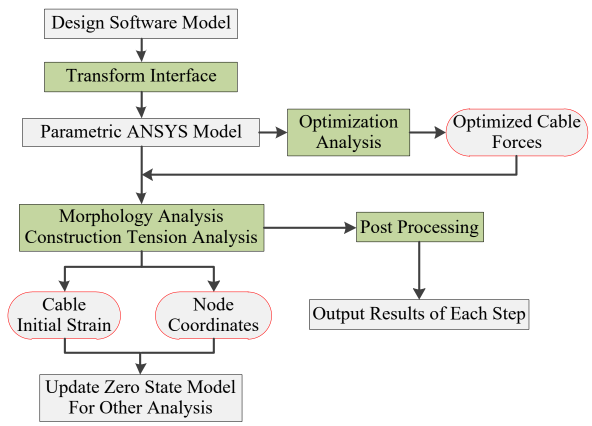

Figure 1. Overall software flowchart.

2.1 Transform Interface Module

The transform interface was used to achieve the transformation of the commonly used models into parametric ANSYS models and analysis data files. The data files included the parameterization information of cables, component definition, construction process definition, iterative analysis control data, etc. The selected element types are listed in Table 1. The temporary construction supports were simplified as compression-only elements by expanding the preset points group. The stiffness values of supports were taken by referring to the actual situation.

Table 1. ANSYS element selection.

Component	Element Type	Characteristic
Latticed shell	BEAM188	3-D, 2-Node Beam
Strut	LINK8	Uniaxial tension-compression spar
Cable	LINK10	KEYOPT(3)=0, Tension only (cable)
Load mass	MASS21	KEYOPT(3)=2, 3-D mass without rotary inertia
Temporary support	LINK10	KEYOPT(3)=1, Compression only (gap)

2.2 Prestress Optimization Analysis Module

Determination of prestress is a key issue in suspend-dome structures. Excessive prestressing can be difficult to implement and the friction drift between cable and joint is considerable, which may even cause the increase in cable force to reach its ultimate tensile forces, while the low prestress cannot satisfy the structural stiffness requirements. In view of other calculative requirements, smaller prestress is preferred due to the fact that it can reduce the difficulty of construction and the cost of the project. Moreover, the ideal prestressed state should meet the following conditions: (1) Ensure that all cables don't relax under normal working conditions; (2) The arch camber caused by prestress can offset the displacement caused by the dead load of the latticed shell; (3) The stress ratios of the latticed shell after forming are as small as possible; (4) The radial displacements of boundary supports are as small as possible.

To solve the problem of prestress determination, the optimization analysis module was developed. Parametric cable forces (p1, p2 ... pn) were defined as DV (design variable). The displacements of the specified points of latticed shell were denoted as SV (state variable), and the maximum stress of the latticed shell elements was extracted as OBJ (objective function). Optimization criteria can be adjusted according to the previous requirements, based upon which the optimal cable force is taken as the target force of subsequent construction tension analysis.

2.3 Construction Tension Analysis Module

The morphology problem involving both structural geometry and prestress distribution is the key issue in the analysis of tensegrity structures, which can be divided into form-finding, force-finding, construction control theory and so on (Zhang 2017). Differing with the flexible structure, suspend-dome exhibits a certain degree of stiffness prior to prestressing. It is required in the morphology analysis that the initial strains of the bottom tensegrity system and the structural form under zero state are to be calculated. The structure varied from zero states to prestress equilibrium state through the redistribution of internal force caused by tension. The cable force caused by initial strain reached a specified target force after prestress loss (Guo *et al.* 2009).

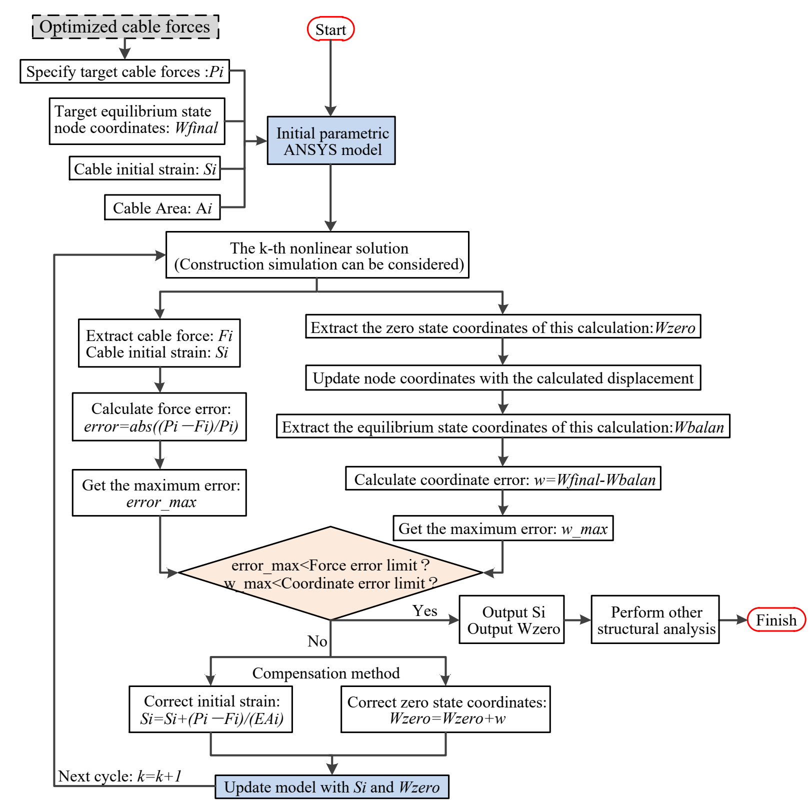

Figure 2. Cycle analysis flowchart.

Based on the actual construction process considering the factors such as temporary supports and additional dead load during construction, this paper performed a complete tension analysis according to the specified construction sequence, the structure form and cable forces under prestress equilibrium state were obtained and compared with the results corresponding to zero state. The above process was defined as a cycle, and iterative analysis would be carried out by correcting the structural form and the initial strains of the cable until reaching the predetermined accuracy. The flowchart is shown in Figure 2. The tension analysis program was developed according to the above process, which can adapt to various construction requirements and can be used to perform the form-finding, force-finding, and construction tension analysis.

2.4 Post Processing Module

There are usually numerous analysis steps and element types in the front tension analysis, and it is important to extract ANSYS results efficiently, especially when comparing with multiple schemes. Therefore, the post-processing module was developed by combining UIDL (User Interface Development Language) and APDL. Hence a menu bar was developed to extracting the results from each step.

3 APPLICATION EXAMPLE

In this paper, a suspend-dome structure from a comprehensive gymnasium was analyzed using the developed software as a working example. The dome has a diameter of 106*m* and a sagittal height of 4.8*m*, supported by 36 radial sliding bearings. The latticed shell and temporary supports are shown in Figure 3. The lower cable-supported system (see Figure 4) was divided into four circles from outside to inside: The struct heights are 5.5*m*, 5.5*m*, 5*m*, 4.5*m*, respectively; The cross-sections of hoop cable are taken as 2×A108*mm*(HC1), 2×A116*mm* (HC2), A66*mm* (HC3), A40*mm* (HC4) and the radial cable is A56*mm* (RC1), A66*mm* (RC2), A50*mm* (RC3), A30*mm* (RC4). The profile is shown in Figure 5. The elastic modulus of cable is equal to $1.9\times10^{11} N/m^2$ and the yield strength is 1670*MPa*. The sections of the latticed shell and struct are A245×12~A420×25*mm*. The sections of the latticed shell and struct are A245×12~A420×25*mm*.

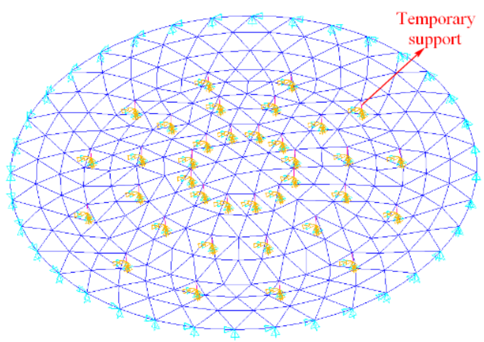

Figure 3. The latticed shell and temporary supports.

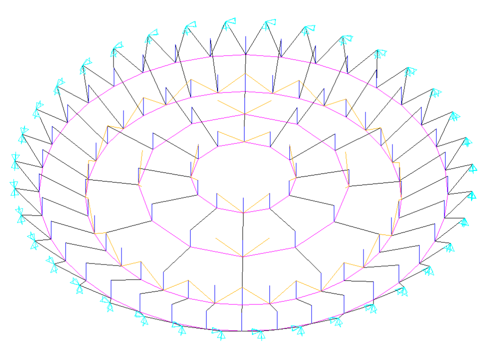

Figure 4. The cable-supported system.

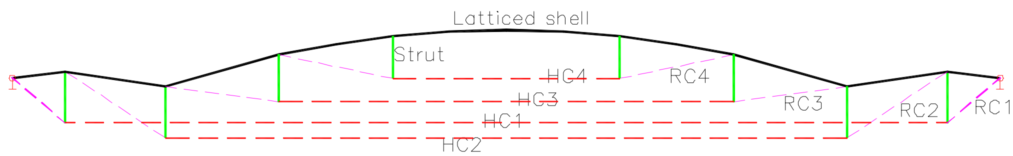

Figure 5. The profile of demo.

The prestress optimization analysis was performed as follows: the hoop cable forces were taken as DV, the max forces were 35% of the breaking loads, the deformation of the latticed shell was restrained, and the minimum stress of the latticed shell was taken as OBJ. The obtained optimized target force results were as follows: HS1=2274.8*kN*, HS2=3283.5*kN*, HS3=293.2*kN*, HS4=40.6*kN*.

The detailed process of the performed construction tension analysis is listed in Table 2. The force finding results are summarized in Table 3, the relevant cloud diagram of cable forces and final deformation are shown in Figure 6 and Figure 7. The form-finding results are output as text files.

Table 2. Definition of construction process.

Step	Construction Contents	Step	Construction Contents
1	Active all temporary supports, assemble latticed shell.	7	Tension HS1 to 100% of the initial pretension
2	Active cables and structs, tension all hoop cables to 5% of the initial pretension	8	Tension HS2 to 100% of the initial pretension
3	Tension HS4 to 80% of the initial pretension	9	Tension HS3 to 100% of the initial pretension
4	Tension HS3 to 80% of the initial pretension	10	Tension HS4 to 100% of the initial pretension
5	Tension HS2 to 80% of the initial pretension	11	Activate the additional dead load
6	Tension HS1 to 80% of the initial pretension	12	Kill all temporary supports

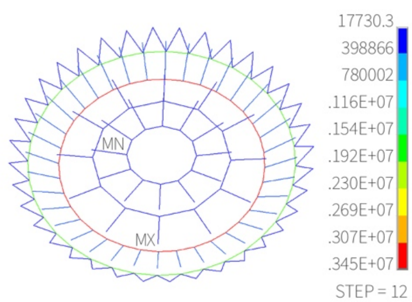

Figure 6. Cloud diagram of cable forces (Step 12).

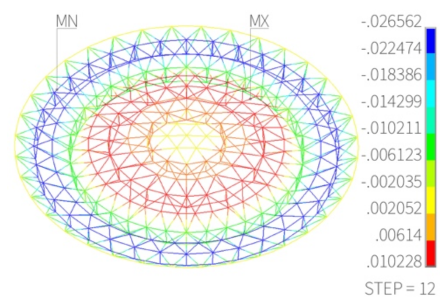

Figure 7. Cloud diagram of deformation (Step 12).

Table 3. Force finding results.

	HC1	HC2	HC3	HC4	RC1	RC2	RC3	RC4
Cable Area / $10^{-6}m^2$	13620	15880	2530	929	1820	2530	1450	522
Target Force / *kN*	2274.8	3283.5	293.2	40.6	—	—	—	—
Actual Force / *kN*	2164.4	3377.3	291.7	40.8	297.3	694.4	154.0	17.7
Relative Error	-4.85%	2.86%	-0.51%	0.49%	—	—	—	—

The force results of each step are summarized in Table 4. The pressure of all temporary supports turned into zero at Step 6, indicating that all temporary supports were separated from the dome and inactive at this step. The maximum cable force during tensioning was 3455.1*kN* at

Step 11, which was about 18% of the breaking load. The maximum latticed shell stress during tensioning was 63.5*MPa* in Step 5 (see Figure 8). The maximum struct force was 88.5*kN* in Step 9 (see Figure 9). The above results revealed that the construction process was controllable and safe.

Table 4. Results of construction process.

Step	HS1 Force/*kN*	HS2 Force/*kN*	HS3 Force/*kN*	HS4 Force/*kN*	Max Latticed Shell Stress/*Mpa*	Max Struct Force/*kN*	Max Temporary Support Pressure/*kN*
1	—	—	—	—	-31.3	—	324.7
2	178.3	157.6	15.8	0.9	-33.6	-8.3	388.3
3	178.1	156.6	15.6	32.0	-33.6	-10.3	387.3
4	177.5	138.7	317.8	30.7	-33.4	-11.3	432.9
5	1000.3	2005.1	203.7	37.4	-63.5	-75.0	93.5
6	1226.1	2044.0	207.7	34.3	-37.8	-73.6	0
7	1260.3	2013.7	209.8	33.6	-37.6	-73.9	0
8	1230.1	2132.6	180.4	35.3	-44.4	-87.3	0
9	1230.9	2120.3	256.0	37.0	-45.6	-88.5	0
10	1230.9	2120.4	256.3	44.1	-45.6	-88.5	0
11	2210.0	3455.1	295.6	41.3	-46.6	-75.1	0
12	2164.4	3377.3	291.7	40.8	-46.2	-75.2	0

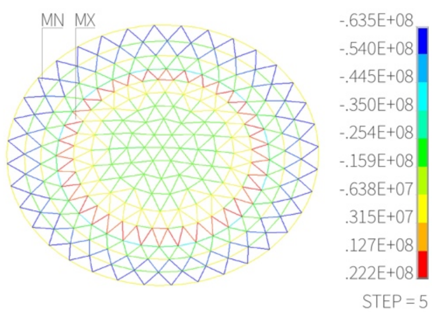

Figure 8. Cloud diagram of latticed shell (Step 5).

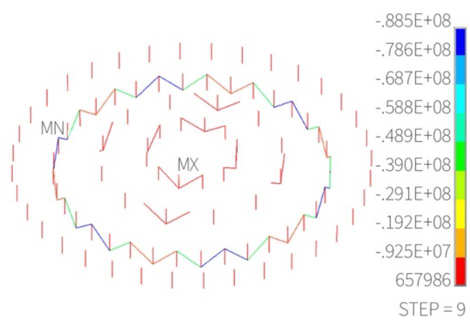

Figure 9. Cloud diagram of struct (Step 9).

4 SUMMARY AND CONCLUSIONS

The analysis of construction tension is particularly important. The feasibility of the construction scheme can be checked, and the control parameters can be provided for the actual construction to ensure smooth construction. The developed software can be used to achieve prestress optimization, morphology, and construction tension analysis of suspend-dome structures.

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