ESTABLISHMENT AND APPLICATION OF CABLE-SLIDING CRITERION EQUATION

Zhihua Chen[1,2], Hongbo Liu[1,*], Xiaodun Wang[1] and Ting Zhou[1]

[1]*Department of Civil Engineering, Tianjin University, Tianjin 300072, China*
[2]*Tianjin Key Laboratory of Civil Engineering Structure & New Materials, Tianjin University, Tianjin 300072, China*
**(Corresponding author: E-mail: hb_liu2008@163.com)*

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ABSTRACT: Based on thermal expansion theory, cable-sliding criterion equations are derived for the static analysis of cable-pulley systems. The friction between cable and pulley is considered in the equations. The cable-sliding criterion equations can govern the sliding motion between cable and pulley. In terms of the governing equations, a few program codes can be easily implemented using the APDL language of ANSYS software. The implemented program is further adopted in the following three examples: the structural behavior of a suspen-dome structure with sliding cable-strut joints; the constructional process of a suspen-dome structure with sliding cable-strut joints and the design of a tree structure. The analytical results show that the cable-sliding criterion equations are effective in describing the sliding motion between cable and pulley.

Keywords: Cable-pulley systems; sliding; friction; suspen-dome structure; tree structure

1. INTRODUCTION

Pulley-cable systems have considerable advantages in the field of engineering, such as structural simplicity, compactness, low friction, absorbing shock and transferring forces. They have been widely employed in cars, cranes, robots, etc.. Furthermore, pulley cable systems are also introduced to spatial structures, such as pre-stressed space truss [1], suspen-dome structure with sliding cable-strut joints [2]. In addition, it has been applied in some structural design processes, e.g., the form finding analysis of tree structure [3].

For the modeling of cable passing through a pulley, Aufaure [4, 5], Zhou [6] and Ju [7] proposed different finite element models to study the deformation and dynamic behavior of structures. The pulley cable systems are included in their study with the assumption of the equal tensions in the cable segments at two sides of a pulley. However, friction exists between cables and the pulley surface [8, 9], which results in different tension values at two side of a pulley. The similar frictional effects have been investigated on rigging slings in a heavy lift system [10-12].

In the finite element models, sliding cable elements are often adopted to investigate the mechanical behavior of structures with pulley-cable systems. However, a large number of program codes are needed in terms of complicated mathematical theory and finite element theory. Therefore, this method is not widely applied in practice. This limitation motivates the study on the cable–sliding criterion equations in this paper. The equations are based on thermal expansion theory to describe the pulley-cable system. In terms of the equations, only a few program codes are needed using APDL language in ANSYS software. The derived equations are easily understood and applied in practice.

2. PULLEY-CABLE SYSTEM SIMULATION IN ANSYS

In general, sliding cable elements are not available in commercial finite element (FE) software packages. However, structures including pulley-cable systems have to be modeled by establishing the sliding cable elements in analysis. The establishment of the elements is considerably difficult in the current commercial FE software packages. In order to overcome the difficulty, thermal expansion theory is adopted in this paper. The basic idea of the theory is that a virtual temperature-increased load is introduced in one-side cable of a pulley, and a virtual temperature-decreased load is applied in another side cable of a pulley. Subsequently, a nonlinear finite element analysis can be conducted using the commercial FE software packages. The modeling of the cable passing through pulleys is achieved. The following is the general procedure to analyze the pulley-cable system in ANSYS:

1) A finite element model is firstly established in ANSYS. Two-node LINK10 elements are adopted to simulate the cable member in pulley-cable systems without considering the sliding behavior between two sides of a pulley.

2) A nonlinear FE analysis is further conducted to obtain the tensions of all cable elements.

3) If the tensions of both side cables of a pulley are not in equilibrium, the cable may slide around the pulley. The sliding lengths around each pulley can be obtained by solving the cable-sliding criterion equations which are to be introduced in the following section. According to these sliding lengths around each pulley, the virtual temperature of both sides of each pulley can be evaluated using thermal expansion theory.

4) After that, a virtual temperature is applied to the corresponding cable element. A re-analysis on the pulley-cable system is fulfilled to obtain the tensions of all cable elements.

5) Finally, the tensions of both sides of pulleys are verified. If they are in equilibrium, the analysis is completed. If not, Step 3 through Step 5 are repeated until the equilibrium is achieved.

3. CABLE-SLIDING CRITERION EQUATIONS

Thermal expansion theory is employed to investigate the cable-pulley system. The critical issue is to accurately obtain the sliding length of cables passing through a pulley. The cable-sliding criterion equations are derived for solving the sliding length of cables passing through a pulley.

3.1 Relationship of the Tensions at Two Sides of a Pulley

Figure 1 shows the tensions in the two cables around a pulley with slip. The inertial effect of the pulley is neglected. The relationship between the tensions at two sides on the edge of slipping is given by Euler’s equation as [13]:

$$T_2 = \alpha T_1, \tag{1}$$

Where the tension ratio α is given as:

$$\alpha = e^{\mu\theta} \quad , \tag{2}$$

Where μ is the friction coefficient and θ is the contact angle as shown in Figure 1. Eq. 1 will be applied to build the relationship between the tensions in the two adjacent cable elements in cable-pulley systems.

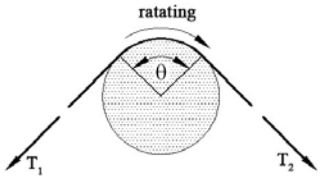


Figure 1. Cable Passing Through a Pulley

3.2 Cable-sliding Criterion Equations for Pulley-cable Systems

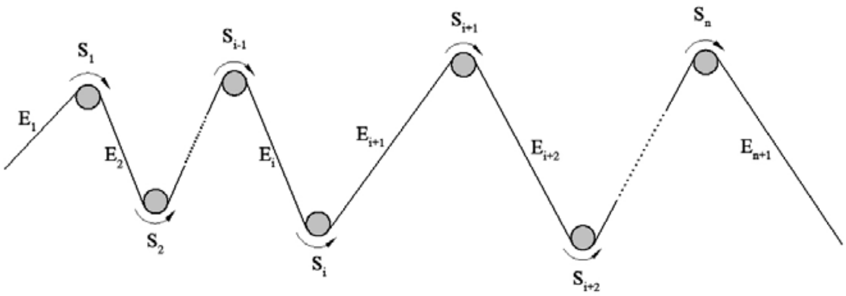


Figure 2. Pulley Cable Systems

Figure 2 gives the diagram for deriving the cable-sliding criterion equations. Symbol $S_i(i=1,2,\cdots,n)$ denotes pulley number, and $E_i(i=1,2,\cdots,n+1)$ denotes cable element number. It is well known that if the force F_i (internal force in cable i) of both sides of a pulley are not in equilibrium, the cable will slide around the pulley until it reaches equilibrium. Based on the deformed model, the force equilibrium equations at each pulley can be obtained as follows.

For Pulley 1 in Figure 2, the force equilibrium is given in Eq. 3a

$$\frac{x_1-\lambda x_n}{l_1}EA_1+F_1=\left(\frac{x_2-x_1}{l_2}EA_2+F_2\right)\alpha \quad . \tag{3a}$$

For Pulley i $(i=2,3,\cdots,n-1)$, the force equilibrium is presented in Eq. 3b

$$\frac{x_i-x_{i-1}}{l_i}EA_i+F_i=\left(\frac{x_{i+1}-x_i}{l_{i+1}}EA_{i+1}+F_{i+1}\right)\alpha \quad . \tag{3b}$$

For Pulley n, the force equilibrium is expressed in Eq. 3c

$$\frac{x_n-x_{n-1}}{l_n}EA_n+F_n=\left(\frac{\lambda x_1-x_n}{l_{n+1}}EA_{n+1}+F_{n+1}\right)\alpha \quad . \tag{3c}$$

Rearranging the force equilibrium Eqs. 3a to 3c, the following equations can be obtained

$$\left[\frac{EA_1}{l_1}+\frac{EA_2\alpha}{l_2}\right]x_1-\left[\frac{EA_2\alpha}{l_2}\right]x_2-\left[\frac{\lambda EA_1}{l_1}\right]x_n=\alpha F_2-F_1 \tag{4a}$$

$$\left[-\frac{EA_i}{l_i}\right]x_{i-1}+\left[\frac{EA_i}{l_i}+\frac{EA_{i+1}\alpha}{l_{i+1}}\right]x_i-\left[\frac{EA_{i+1}\alpha}{l_{i+1}}\right]x_{i+1}=\alpha F_{i+1}-F_i \tag{4b}$$

$$\left[-\frac{\lambda EA_{n+1}\alpha}{l_{n+1}}\right]x_1+\left[-\frac{EA_n}{l_n}\right]x_{n-1}+\left[\frac{EA_n}{l_n}+\frac{EA_{n+1}\alpha}{l_{n+1}}\right]x_n=\alpha F_{n+1}-F_n \tag{4c}$$

where x_i = sliding length of the cable at Pulley i $(i=1,2,\cdots,n)$.
$\lambda =$ type number of the cable-pulley system. If the cable-pulley system is open-loop, $\lambda=0$; If the cable-pulley system is closed-loop, $\lambda=1$.
A_i = the section area of cable element i $(i=1,2,\cdots,n,n+1)$.
E = the elastic modulus of a cable element.

Eqs. 4 are the cable-sliding criterion equations, and the sliding length x_i of cable at Pulley i can be obtained by solving Eqs. 4. Then the length variation value of each cable element can be evaluated by the following equations, respectively:

for $\lambda=0$ $\quad (x_1),(x_2-x_1),\ldots,(x_i-x_{i-1}),\ldots,(x_n-x_{n-1}),(-x_n)$ (5a)

for $\lambda=1$ $\quad (x_1-x_n),(x_2-x_1),\ldots,(x_i-x_{i-1}),\ldots,(x_n-x_{n-1})$ (5b)

Moreover,

for $\lambda=0$ $\quad (x_1)+(x_2-x_1)+\ldots+(x_i-x_{i-1})+\ldots+(x_n-x_{n-1})+(-x_n)=0$ (6a)

for $\lambda=1$ $\quad (x_1(-x_n))+(x_2-x_1)+\ldots+(x_i-x_{i-1})+\ldots+(x_n-x_{n-1})=0$ (6b)

Therefore, it is verified that the sliding length x_i of the cable at pulley i is obtained by solving the cable-sliding criterion equations. The equations satisfy the compatibility requirement of displacement. In other words, the original length is not changed. The virtual temperature loads of each cable element can be calculated in terms of Eqs. 7.

For cable element 1： $-\alpha_T \Delta T_1 L_1=\Delta L_1=x_1-\lambda x_n$ (7a)

For cable element $i=2\sim n$： $-\alpha_T \Delta T_i L_i=\Delta L_i=x_i-x_{i-1}$ (7b)

For cable element $n+1$： $-\alpha_T \Delta T_{n+1} L_{n+1}=\Delta L_{n+1}=\lambda x_1-x_n$ (7c)

The cable sliding around a pulley can be realized by applying these virtual temperature loads on all cable elements. For the cable-pulley systems in Figure 2, the structural analysis of all fixed pulleys can be done in one iteration using the proposed cable-sliding criterion equations. Only a few iterations are needed if the pulleys are movable. In a word, the cable-sliding criterion equations provide an easy way for the structural analysis of cable-pulley systems. The results are accurate with rapid convergence. Therefore, the cable-sliding criterion equations can be widely applied in practice.

4. MULTI-LINE PULLEY-CABLE SYSTEMS

In the case of single cable-pulley systems, e.g., crane structures, beam string structures, cable-sliding criterion equations easily fulfill the task with well convergence. However, when multi-line cable-pulley systems are considered, such as suspen-dome structures, additional factors have to be considered as follows

1) In multi-line cable-pulley systems (e.g., suspen-dome structures with several single cable-pulley systems), the interference among each single cable pulley systems is very remarkable. For this type of systems, the convergence rate of cable-sliding criterion equations is slow and some solutions even disconverge in some cases.

2) Geometric nonlinearity of multi-cable pulley system is usually significant, which results in the slow convergence rate of the cable-sliding criterion equations.

In order to solve the above two problems, the following measures are adopted:

1) For the first problem, it can be solved by evaluating the virtual temperature firstly and applying the obtained virtual temperature to the corresponding cable pulley system one by one.

2) For the second problem, the solution process is divided into several steps. In each step, the amplification factor of the obtained virtual temperature is adopted according to different precision in each step.

As an illustrative example, the solution process of cable-sliding criterion equations is given in details for suspen-dome structure. The suspen-dome structure is a multi-cable pulley system.

1) A FE model is established using universal elements BEAM188, LINK8, and LINK10 in the commercial software package ANSYS. The assumption is made that the cable cannot slide around pulley;

2) A nonlinear analysis is conducted with the FE model. Both the material nonlinearity and geometric nonlinearity are considered;

3) Before the analysis, a precision $error\_1$ is preliminarily set for the first step of the analysis (two steps are set in this example as well as two precisions);

4) The inner force F_i^j of each cable element is obtained, where i denote the cable number and j denote the number of cable pulley system;

5) The unbalanced force at each pulley is evaluated. If the $MAX\left(\left|\Delta F_i\right|\right) \leq error\_1$, the current iteration of cable sliding is completed and then the computation goes to Step (7), or else the computation continues by Step (6);

$$\Delta F_i = \left|F_{i+1} - \alpha F_i\right| \tag{8}$$

6) If $MAX\left(\left|\Delta F_i\right|\right) \geq error\_1$, cable will slide around pulley until the system reach equilibrium. Using the proposed cable-sliding criterion equations, the virtual temperatures of each cable element are calculated and applied to the corresponding cable element to realize cable sliding around pulleys. It is noted that in order to obtain a well convergence, the virtual temperature of each

cable pulley system are calculated and applied to the corresponding cable element one by one by an amplification factor φ. In other words, the virtual temperature of the first cable pulley system are calculated and applied firstly by multiplying amplification factor φ and then for second cable pulley system, third cable pulley system … and then return to step (4). In addition, the factor φ can be taken to 1.0~2.0 by experience;

7) The second step iteration is carried out and set precision as control $error\_2$. Because two steps were set, $error\_2$ must be an allowable value for practical purpose (if number of step is more than two, the control precision of last step must be allowable in practice). According to the analysis method in the first step, a structural analysis is carried out. It is noted that the amplification factor φ of virtual temperature must be 1 in the last step iteration.

5. VERIFICATION

In this section, a static analysis of a continuous cable passing two pulleys is conducted to verify the proposed cable-sliding criterion equation. The system is shown in Figure 3. One end of the cable is connected to a winch with a pulling force of 80kN. The other end is connected to a structure member or a payload. The force and displacement boundary conditions are also indicated in Figure 3. The diameter and Yong's modulus of the cables are assumed to be 26mm and 50 kN/mm^2, respectively. The example is the same as that in Ref. [10].

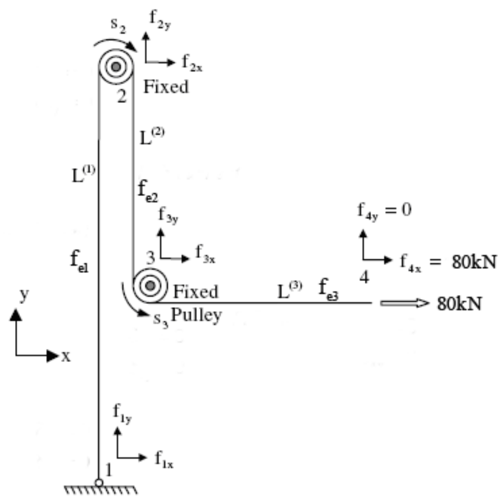


Figure 3. A Continuous Cables Passing through Two Fixed Pulleys

Result 1 in Table 1 is given by the proposed method in this paper and Result 2 is evaluated by the formulae presented in Ref. [10]. Comparisons show that the results of the proposed method agree well with the results given by Ref. [10]. Therefore, the proposed method is effective to analyze the cable pulley system by using the cable-sliding criterion equations.

Table 1. Summary of the Analysis Results

Item	F_{1y}	F_{2y}	F_{3y}	S_1	S_2	δ
Result 1	19.47kN	69.41kN	49.94kN	3.67mm	9.31mm	15.34mm
Result 2	19.47kN	69.42kN	49.95kN	3.67mm	9.31mm	15.34mm
Error	0	0.01	0.02	0	0	0

6. NUMERICAL EXAMPLES AND DISCUSSIONS

6.1 Example 1: Behaviors of Suspen-dome Structure with Sliding Cable-strut Joints

Suspen-dome structure is a pre-stressed spatial structure. It has higher stiffness than that of single layer lattice shell. Also, the construction of suspen-dome structure is more convenient than that of cable dome. Suspen-dome structure has been widely applied as roof structures in many buildings, such as Hikarigaoka dome and Fureai dome in Japan, Badminton Gymnasium for 2008 Beijing Olympic Games in China, and Jinan Olympic sports center's gymnasium for the 2009 11th National Olympic Games in China [14].

In the design of suspen-dome structure, a critical issue is the choice on the type of cable-strut joints. In practice, two kinds of cable-strut joints are usually considered. One is non-sliding cable-strut joint as shown in Figure 4, and the other is sliding cable-strut joint as shown in Figure 5. If the first type is adopted, the two adjacent hoop cables are independent and the hoop cables cannot slide around joints. Comparatively, if the second type is adopted, each circumference hoop cable is a continuous cable and the hoop cable can slide around joints. Due to the convenience and low cost of the second type, the continuous cable sliding around joints are preferred in most structures.

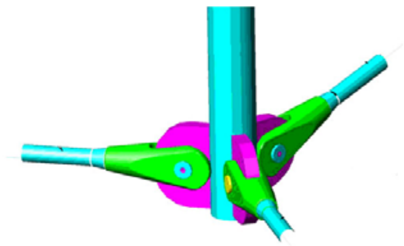
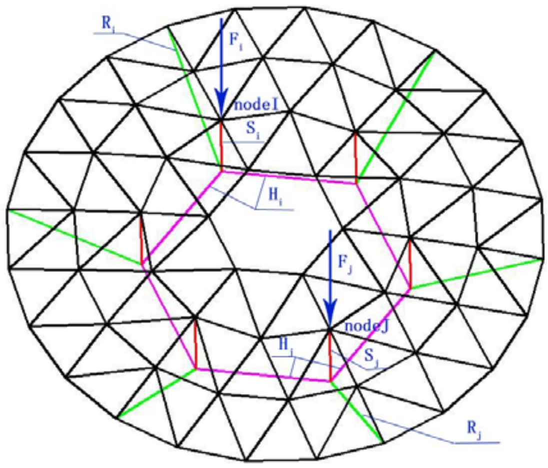


Figure 4. Non-sliding Cable-strut Joint

Figure 5. Sliding Cable-strut Joint

In addition, a previous reference reports that the suspen-dome structure with sliding cable-strut joint can carry the asymmetric loads more efficiently than the suspen-dome with non-sliding cable-strut joint does [2]. In contrast, we propose that the suspen-dome structure with non-sliding cable-strut joint is better than the suspen-dome structure with sliding cable-strut joint under asymmetric loads. Our reason is illustrated in Figure 6. Forces F_i and F_j denote concentrated vertical forces applied at node I and J, and $F_i > F_j$.



black line: single layer lattice shell; red line: struts; green line: radial bars; pink line: cables

Figure 6. Force Schematic Diagram of Suspen-dome

Assuming that the hoop cable cannot slide around cable-strut joints, it is obvious that the vertical displacement of Node I and the inner forces of the neighboring members connected to Node I are larger than those of Node J. If the hoop cable can slide around cable-strut joints with free-friction, the cable will slide around cable-strut joints until the cable forces in cable element are in equilibrium. Compared with the former case, the inner force of the hoop cable element below Node I will decrease and the inner force of hoop cable element below Node J will increase when the hoop cable can slide around cable-strut joint with free-friction. Subsequently, in one hand, the vertical displacement of Node I, the inner force and moment of members connected to Node I will increase until being in equilibrium; in the other hand, the vertical displacement of Node J, the inner force and moment of member connected to Node J will decrease until being in equilibrium. Therefore, the maximum inner force and maximum node displacement of the suspen-dome structure is much larger when the hoop cable can slide around cable-strut joint with free-friction.

The following example further confirms our opinion. Here, Chiping Gymnasium is analyzed, whose roof is a suspen-dome system. The schematic view of the structural system is shown in Figure 7. Detailed information about this structure can refer to Ref. [15]. Due to the existence of arches and solar radiation action, the loads of the suspen-dome system is very non-uniform. In this analysis, the friction is not considered such that the tension ratio α in Eqns. (4) is equal to 1.

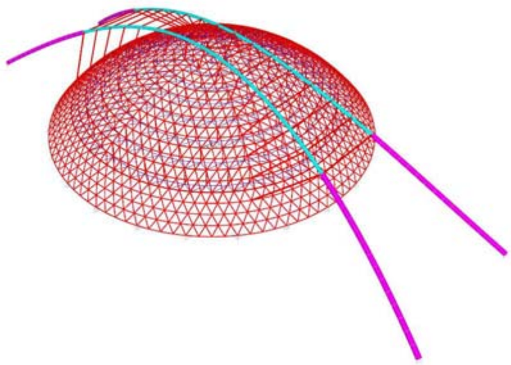


Figure 7. A Schematic View of Structural System of Chiping Gymnasium

Table 2 presents maximum values, minimum values, average values, deviations between maximum value and average value as well as deviations between minimum value and average value. Case 1 gives the results when the hoop cable cannot slide around cable-strut joint and Case 2 gives results when the hoop cable can slide around cable-strut joint with free-friction. Table 2 shows that the inner force in each hoop cable is very non-uniform, especially for 1~ 4 hoop cables and the maximum deviation can reach 190% for Cable Group 1.

Table 2. Distribution of Cable Force when Hoop Cable is Noncontinuous

Cable groups		1	2	3	4	5	6	7
Case 1	Minimum force (kN）	0.53	14.76	53.15	322.70	584.29	1075.82	1851.65
	Maximum force (kN）	198.02	111.15	193.72	447.76	698.86	1165.11	2085.72
	Average force (kN）	68.23	57.84	130.98	392.80	644.45	1117.72	1976.50
	Maximum deviation (%)	190	92	59	18	9	4	6
Case 2	Cable force	74.27	65.97	140.89	393.09	648.09	1112.60	1920.20

Note: Cable group 1 is outmost hoop cables, and Cable group 7 is the innermost hoop cables

The distribution of maximum equivalent stress for both Case 1 and Case 2 are given in Table 3. From Table 3, the maximum equivalent stress of Case 2 is larger than that of Case 1, which shows the mechanical behavior of Case1 is better than that of Case 2. Compared with the maximum equivalent stress of 129 MPa and the maximum node displacement of 68 mm of Case 1, the corresponding values of Case 2 are 230MPa (77% increased) and 135 mm (96% increased), respectively. Therefore, The suspen-dome of with non-sliding cable-strut joint is better in mechanical behavior when the structure carries asymmetric loads.

Table 3. Distribution of Equivalent Stress of Each Suspen-dome Member with Stacked Arch Model

	0~50 (MPa)	50~100(MPa)	100~150(MPa)	150~200(MPa)	≥200(MPa)
Case 1	3134	1049	41	-	-
Case 2	2639	1244	233	48	60

6.2 Example 2: Numerical Simulation on the Pre-stressing Construction Process of Suspen-dome Structure

A finite element model of a suspen-dome structure is established to study the effect of friction between cables and cable-struts during the pre-stressing construction. This suspen-dome structure is with a span of 35.4 m and a rise of 4.6 m. Steel pipes of ϕ133mm×6mm are used as the principal members of the upper single layer shell, and steel pipes of ϕ89mm×4mm are used as vertical struts. One radial cable (6×19ϕ18.5) and one hoop cable (6×19ϕ24.5) are arranged in the bottom of the structure. The elastic modulus of steel pipes and cables are 2.1×10^5 N/mm^{2}and 1.8×10^5N/mm^2, respectively. The boundary conditions are that the vertical and tangential displacements are restricted with unrestricted radial displacement. The pre-stresses of hoop cables are uniformly set as 100kN. The finite element model is shown in Figure 8.

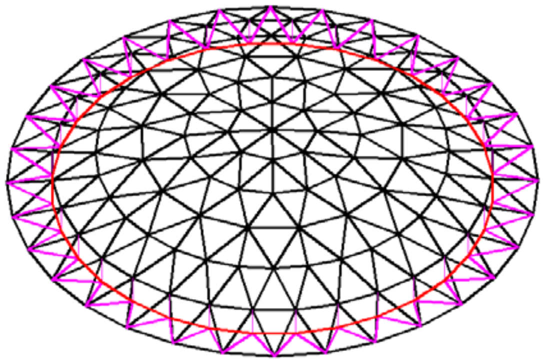


Figure 8. Finite Element Model of Suspen-dome of Tianbao Center

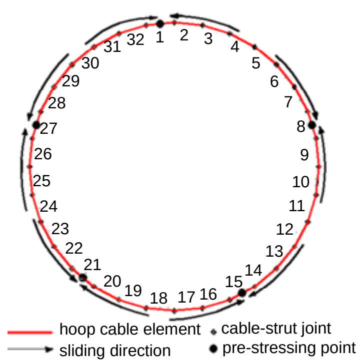


Figure 9. Schematic Diagram for Sliding Direction and Number of Cable Element

The coefficient of friction between cables and cable-struts is assumed as 0.4 [16, 17]. In terms of the shape of cable-strut joint, the tension ratio α for hoop cables at cable-strut joint is 1.08. The five pre-stressing points for the hoop cable system are set as shown in Figure 9. Because only one hoop cable is adopted in the structure, the pre-tensioning control value is 100kN if the friction between cable and joints is not considered.

In order to study the effect of friction, the numerical analysis is carried out using the proposed cable-sliding criterion equations. Firstly, the FE model (Figure 8) is established using the node coordinates of the zero state geometry obtained from the modified cyclic iteration and initial length control methods [18]. Secondly, the effect of friction is considered and the numerical simulation analysis of the construction procedure is carried out using the same cable-sliding criterion equations. The maximum inner force, minimum inner force, deviation between calculated force and design force are obtained from the FE analysis and they are 79.5kN, 100kN, and 20.48%, respectively. The average pre-stress loss is 6.83% for each cable-strut joints in the hoop cable system, which agrees well with the experiment results of the Badminton Gymnasium of 2008 Beijing Olympic Games [16, 17]. The deviations between calculated force and design force are shown in Figure 10 and it can be concluded that the friction has a significant effect on the pre-stressing construction.

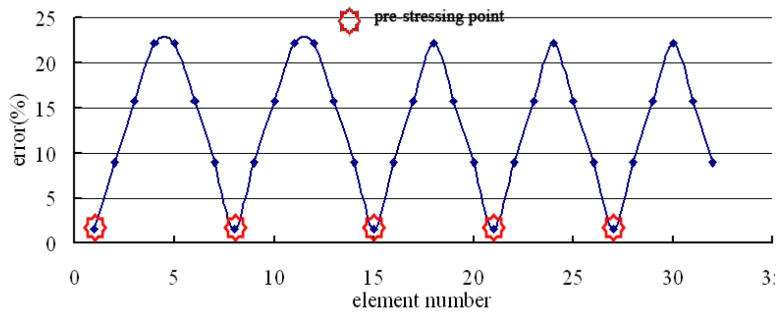


Figure10. Deviations for Each Hoop Cable Element

6.3 Example 3: Design of Tree Structure

Tree structures provide an efficient way to transfer large surface loads to a single point on the ground. They have been widely used in architecture and structure. The branches of the tree are arranged so that only tension and compression forces exist under the applied loads, which results in smaller member cross-sectional areas and a minimal amount of materials. Additionally, hanging models are the traditional method to determine the equilibrium shape of tree structures. A hanging model of the tree structure is created with flexible threads or chains. The thread or chain is suspended and secured together at certain points (branching nodes) so that it can rotate freely at the intersection. The equilibrium shape resulting in purely axial forces can be found because the thread or chain is capable of supporting only tension forces.

The traditional method can obtain the optimal shape of tree structures, but the procedure needs much time. Therefore, a computational algorithm, which can obtain the best shape of tree structure with a little time, is desired. The proposed cable-sliding criterion equations can provide such an algorithm because it can simulate the sliding of chain passing nodes. To show the cable-sliding criterion equations are applied in the design of tree structure, an example is designed.

The initial form is shown in Figure 11, and Node 1, Node 2 and Node 3 are sliding nodes. In other words, Line1 and Line 2 can rotate freely at the Node 1; Line3 and Line 4 can rotate freely at the Node 2; Line5 and Nine 6 can rotate freely at Node 3. Using the traditional method, the initial form of tree structures is built using threads and all nodes are fixed using thumbtacks as shown in Figure 12. Then thumbtacks at Node 1, Node 2 and Node 3 are removed and Line 1 and Line 2, Line 3 and Line 4, and Line 5 and Line 6 can rotate freely at Node 2, Node 3 and Node 4, respectively. Meanwhile, Node 4 is moved along the vertical direction until all threads are tightened. The final shape of the tree structure is shown in Figure 13 and it is the optimum shape of the tree structure obtained from the traditional method.

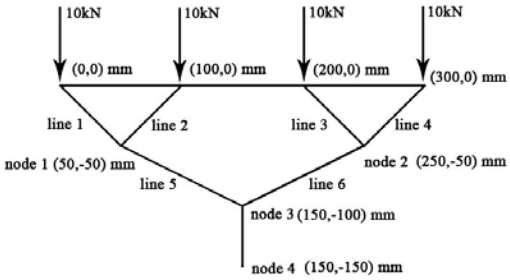


Figure 11. Initial Shape of Tree Structure

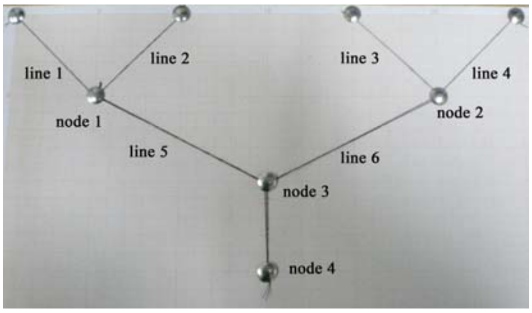


Figure 12. Initial Shape of Tree Structure of Traditional Method

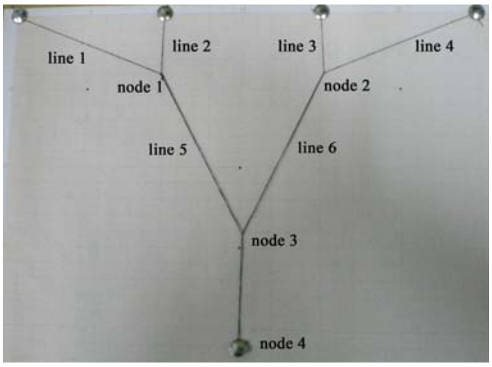


Figure 13. Best Shape of Tree Structure from Traditional Method

Using the proposed cable-sliding criterion equations (4) in this paper, the process of the traditional method is simulated and the result is shown in Figure 14. Compared with the optimum shape obtained from the traditional method as it shown in Figure 13, the optimum shape obtained using cable-sliding criterion equations is well consistent and therefore, cable-sliding criterion equations can be used to determine the optimum shape of tree structure.

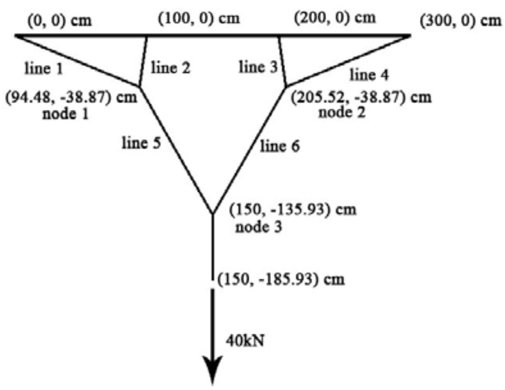


Figure 14. Best Shape of Tree Structure from FEM Analysis

7. CONCLUSIONS

A group of cable-sliding criterion equations for simulating a cable passing through multiple pulleys is proposed in this paper. The proposed method is firstly evaluated by a simple cable system with three fixed pulleys. The obtained results satisfy the static equilibrium and deformation compatibility conditions of the structural system and basic engineering principles. Then the cable-sliding criterion equations are further applied to three practical engineering systems: a suspen-dome structure with stacked arches, a constructional numerical simulation of suspen-dome structure and a tree structure design.

Numerical analysis for a suspen-dome structure with stacked arches shows that the suspen-dome structure with non-sliding cable-strut joints is better than the suspen-dome with sliding cable-strut joint under asymmetric loads. Therefore, the non-sliding cable-strut joint is proposed for the future suspen-dome design.

Numerical simulation of the construction process of a suspen-dome structure shows that the friction between hoop cables and cable-strut joints has a significant effect on the pre-stressing construction. Therefore, some additional measures are suggested, such as to amplify the pre-tensioning control value of loop cables, to increase the pre-stressing points and to decrease the coefficient of friction between cable and cable-strut joint.

A design example of a tree structure shows that the cable-sliding criterion equations serve as a useful tool for designing spatial tree structures.

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