Double control method for construction form finding of glass curtain system

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Abstract: An incremental equilibrium equation was deduced for the construction of glass curtain system with inverted-cone curved single-layer cable-net based on the theory of non-linear finite element method. In view of actual influence of glass installation during the construction process, analysis is made on the correction algorithm for formation of non-linear stiffness matrix of structure with consideration of glass installation. The developed algorithm allows for double control over the shape and pre-tension during the construction, and accurate determination of the structural configuration and cable force. Feasibility and accuracy of the method are verified and supported by the case study results.

1. Introduction

Glass curtain system with single-layer cable-net is of the structure of point supported glass curtain wall, and is a structural system consisting of main load-bearing members - the suspension cables arranged according to certain rules [1]. The application of glass curtain system with single-layer cable-net is currently ahead of the study. The system can be divided into a single-layer cable-net system and a single-cable system. Glass curtain system with cable-net is of a semi-rigid structure, with a large geometric nonlinearity. Therefore, during the construction process, all the tensioning sequence of the cable, the tension level and the installation order of the glass after tension have an effect on the internal force distribution and shape of the structure.

At present, studies on the construction form finding of glass curtain system with single-layer cable-net mainly focus on the cable-net system [2-6]. To find the construction layout state that conforms to the shape and the cable internal force in designed state is challenging [7]. In literature [8], the curtain wall project of Dongguan Basketball Center was discussed. However, the cable force and shape in construction layout state were not studied. Meanwhile, literature [9] analyzed the cable force in construction layout state of glass curtain system with cable-net, which actually is a single control method that only controls the cable force. In summary, there is few studies on construction layout state of the
glass curtain system with cable-net and construction form finding, and systematic shape is mainly controlled via the shape design of the cable-supporting structure [3].

The analysis on construction form finding of engineering structure shall be conducted in conjunction with structural construction process and construction technology, generally, by stretching-drawing the cables and grading the batches [10-13]. Stretching-drawing cables of latter grades and batches always change the tension force of cables of all the former grades and batches, further change the structural shape. Both the construction process and the construction technology affect the final cable force and configuration of the structure [14], and more studies have been done combining tension system structure at home and abroad [15-20]. The differences in structural systems limit the application of the above study results in the glass curtain system with cable-net.

The construction control study on the glass curtain system with cable-net is different from that on other types of tension systematic structure. Firstly, the glass curtain system with cable-net is of a semi-rigid structure. Therefore, it’s necessary to adopt the double control method of finding force and form at the same time during the construction. The effect of geometric nonlinearity should also be considered. Secondly, in the single-layer cable-net supported system, the stress state of the glass member connected position will impose new effect to the system construction form finding [21]. However, current study on the influence of glass installation on the structural system mainly focuses on the cooperative bearing of glass and main structure after the construction forming [6].

In view of paper, based on the tangible impact of geometric nonlinearity and glass installation on the construction process of glass curtain system with cable-net, establishes the correction algorithm for formation of non-linear stiffness matrix of structure with consideration of glass installation, whereby a servo construction method is proposed which is based on double control of shape and cable force, and takes glass installation into consideration. Such a method allows for double control over the shape and pre-tension during the construction and acquirement of accurate structural configuration and cable force which agree with those in designed state according to the final state of construction forming.

2. Double control theory of construction form finding

During the construction of the glass curtain system with single-layer cable-net, with the number of rope members increases, the structural stiffness matrix and load array are constantly changing. For a certain stage, $i$, and that at the previous construction stage (the $(i-1)$ stage):

$$\{d\} = \{d^{-1}\} + \{\Delta d\}$$

(1)

Where, $\{d^{-1}\}$ and $\{\Delta d\}$ are the structure node displacement at stage $i$ and the previous stage of the construction; $\{\Delta d\}$ is the increased displacement of node at the $i$ stage.

$$\{a\} = \begin{bmatrix} a_i \\ a_i^{-1} \end{bmatrix}, \quad \{\Delta a\} = \begin{bmatrix} \Delta a_i \\ \Delta a_i^{-1} \end{bmatrix}$$

(2)

Based on the structural tangent stiffness matrix, and the corresponding incremental finite element equation established can be rewritten as an incremental form:

$$\left[K_i(a')\right]\{\Delta a\} = \{\Delta F_i\}$$

(3)

Since the stiffness matrix is relevant to the node displacement, the structural tangent stiffness matrix may be updated:

$$\left[K_i(a')\right] = \left[K_i^{-1}(a')\right] + [\Delta K_i(a')]$$

(4)

Where, $\left[K_i\right]$ and $\left[K_i^{-1}\right]$ are the structural tangent stiffness matrixes at stage $i$ and $i-1$ of the construction process; $[\Delta K_i(a')]$ indicates the tangent stiffness matrix of the newly added part of the structure at the $i$ construction stage.
The corresponding incremental finite element equation can be written as an incremental form:

$$ \{K_a'(\Delta u')\}[\Delta u'] = -\{\Delta F\} $$

(5)

With the node displacement \(\{u_i'\}\) obtained above, the node coordinates, \(\{X_i\}\), is calculated

$$ \{X_i\} = \{X_i'\} + \{u_i'\} $$

(6)

where, \(\{X_i'\}\) is the node coordinates in structural layout state at stage \(i\) in the construction process, which is obtained by updating node coordinates, \(\{X_i^{i-1}\}\).

The key step for analysis is to find the appropriate construction layout state node coordinate \(\{X_i\}\) and initial strain \(\{\varepsilon\}\). The steps for iterative computation of \(\{X_i\}\) and \(\{\varepsilon\}\) are detailed below. In the first step of the iterative calculation, they are obtained using the following equation:

$$ \{X_i\}_0 = \{X_i\}_0' - \{T\}_i / (E_i A L_i) $$

(7)

The initial displacements of the nodes of the cable element \(\{a_i\}_0\) are respectively determined by

$$ \{a_i\}_0 = L_i \{\varepsilon_i\}_0 $$

(8)

Where, the \(E_i\), \(A_i\), and \(L_i\) are the elastic modulus, area, and length of the cable respectively. and the convergence condition of the computation iterative step as follows

$$ e_i \leq \delta_1 \text{ and } e_i \leq \delta_2 $$

(9)

Here, \(\delta\) is the convergence tolerance.

3. Analysis of construction form finding by double control method

3.1. Numerical model
The truss and batter post are composed of circular steel pipes and their elastic modulus is \(2.06 \times 10^5\) MPa, the section area and inertia moment of truss are \(A_1=100767\) mm$^2$, \(I_1=1.44 \times 10^{10}\) mm$^4$, \(A_2=63096\) mm$^2$, \(I_2=3.54 \times 10^9\) mm$^4$, \(A_3=15774\) mm$^2$, \(I_3=2.21 \times 10^9\) mm$^4$, \(A_4=4394\) mm$^2$, \(I_4=1.08 \times 10^7\) mm$^4$, \(A_5=117012\) mm$^2$, \(I_5=1.66 \times 10^{10}\) mm$^4$; the batter post’s section parameters are \(A_7=100767\) mm$^2$, \(I_7=1.44 \times 10^{10}\) mm$^4$; the stay cable’s section type is steel strand and its elastic modulus and section parameters are \(1.35 \times 10^5\) MPa, \(A_8=2392\) mm$^2$, \(A_9=1890\) mm$^2$, \(A_{10}=1530\) mm$^2$ respectively.

3.2. Construction form finding by force control method
When calculated by the force control method, the error between the cable force in forming state and the target cable force is relatively small, and the maximum is 5.95\%, which does not meet the engineering accuracy requirements.

3.3. Construction form finding by the double control method
Since the force control method only meets the need for the high-precision cable force searching and is difficult to meet the need for the high-precision structural shape, so it is necessary to perform the analysis of construction form finding by double control method. Figure.1 shows the initial strains and the cable forces in the forming state calculated by the force control method. It is known from the figure that the error between the cable force in the forming state and the target cable force is negligible, and the maximum is 0.42\%, which meets the engineering accuracy requirements. Figure.2 shows the geometric configuration of the forming state obtained by the force control method. The errors between the configuration and the design values are relatively small, in which the maximum is 7 mm.
4. Concluding remarks
In this paper, the construction form finding by double control calculation method based on cooperative bearing of glass and cable is proposed for the glass curtain system with curved single-layer cable-net, and corresponding construction form finding by double control method is developed for the pre-stressed construction of the system. The analysis on double control method are carried out by a case study on the construction of a cable glass curtain wall of Nanning Airport. The results show that the proposed double control method has high accuracy which may meet the requirements of the design state on the cable force and structural configuration. Therefore, construction form finding by double control method is feasible and effective.

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