Engineering Structures 110 (2016) 184–208

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A specific rod model based efficient analysis and design of hanger installation for self-anchored suspension bridges with 3D curved cables

Yuan Sun [a,*], Hong-Ping Zhu [a], Dong Xu [b]

[a] School of Civil Engineering & Mechanics, Huazhong University of Science and Technology, Wuhan, Hubei, PR China
[b] School of Civil Engineering, Department of Bridge & Tunnel Engineering, Tongji University, Shanghai, PR China

ARTICLE INFO

Article history:
Received 19 December 2014
Revised 24 November 2015
Accepted 26 November 2015
Available online 29 December 2015

Keywords:
Hanger installation
Construction step analysis
Numerical algorithms
Nonlinear finite element method
Suspension bridge
Unstrained length

ABSTRACT

Hanger installation is important in constructing self-anchored suspension bridges. The installation plan is obtained from comparative studies of concerned information in tentative construction steps. The comparisons are generally performed manually using detailed nonlinear finite element method (NFEM), particularly for those with 3D curved cables. However, the procedure is complex and time consuming. Thus, this study proposes an efficient method to analyze mainly concerned parameters of hanger installation plan, through which automatically optimized strategy of updating ideal construction steps is developed to yield the plan totally by linear coordinate iteration. To realize it, an indiscrimination coordinate rod model (ICRM) combined with coordinate iteration-based methods (CIMs) is proposed for the modeling of the construction steps. The ICRM simulates the major deformation system of the total bridge with specific rods, and then the CIMs identify its equilibrium by linear algorithms to solve the coordinates directly. On the basis, NFEM can be avoided and the design efficiency is greatly improved for the plan. The effectiveness of the proposed method is demonstrated by comparison case studies, field test verification and application discussion in a real-scale bridge.

1. Introduction

Self-anchored suspension bridges with 3D curved cables, such as Yongjong Grand Bridge [1] and San Francisco–Oakland Bay Bridge [2], belong to novel type of bridge structure with several modern applications. Similar bridges in China [3–5] have likewise been constructed or are under planning. The profile of the 3D curved cable system of this bridge structure is neither on a vertical nor a horizontal plane. It indicates that more computational and manual efforts are required for easier divergence is exhibited in nonlinear calculations of such a structure. Particularly, the cable shape must be considerably changed during the construction stage. This requirement introduces strong nonlinearity and complicates the determination of construction schemes, including the hanger installation plan.

A hanger installation plan provides critical information on the construction of a self-anchored suspension bridge. The steps in constructing such a bridge, similar with extradosed cable stayed bridges [6,7], are to erect the stiffening girder, air-spin the main cable, and then install each hanger between the main cable and the deck. At this juncture, the hanger installation plan should be determined to guide installation of hangers in terms of stretching forms, installation sequence, and predetermined unstrained lengths of hangers under the conditions of safety and economic requirements. Traditional analytical methods based on deflection theories [8–10] are not readily applicable for design of such structures. Thus, the determination of the plan has elicited considerable research attention; various methods based on catenary element [11–14] and the nonlinear finite element method (NFEM) have been developed [15–20]. Kim et al. [21] determined a hanger installation plan through comparative studies. They utilized elastic catenary cable elements to model the main cables and hangers and first proposed a six-step construction plan by utilizing synchronized and divided tension work through various attempts. A rigorous backward/forward construction step analysis was performed to limit the maximum jacking force to below the jacking capacity. The plan was applied successfully to the construction of the Yongjong Grand Bridge. Subsequently, some researchers adopted this idea of manual comparisons and provided revised methods by integrating additional conditions or auxiliary algorithms. Li et al. [5] considered the extrusion between hangers and anchor tubes by employing excessive comparative studies. Yang and Shen [22] utilized the influence matrix method to support the NFEM-based construction step analysis for bridges with 2D cable system. Tan

* Corresponding author. Tel.: +86 13871217571; fax: +86 27 87840630.
E-mail addresses: sunxiao_1981@126.com (Y. Sun), hpzhu@mail.hust.edu.cn (H.-P. Zhu), xu_dong@tongji.edu.cn (D. Xu).

http://dx.doi.org/10.1016/j.engstruct.2015.11.040
0141-0296/

[23] proposed an analytical element method for a 3D cable system in construction, wherein the hanger sheaths were regarded as a system of particle equilibrium in consideration of tensile stiffness. The equilibrium equation was solved using displacement step length.

As aforementioned, a proper hanger installation plan can be constructed by comparing the construction steps of various tentative installation procedures under predefined constraints, such as allowable tension limits and construction conditions. Manually comparing construction steps using NFEM is inefficient in the FE model of a whole self-anchored suspension bridge, particularly those with 3D curved cables. Hence, methods that support NFEM to promote the computational efficiency of construction step analysis or that avoid the inefficient part of NFEM are desirable. Several strategies combined with NFEM have been recently proposed to obtain satisfactory results in the initial shaping analysis of self-anchored suspension bridges [24–29]. However, these strategies cannot be readily extended to analyze the construction step of a 3D cable system and to determine the hanger installation plan of such structures because of their limitations. These limitations include easy divergence and complex procedures when applied to a whole bridge system; additionally, these strategies only consider hangers perpendicular to the longitudinal direction.

To address these issues, this study proposes an alternative efficient method to analyze mainly concerned parameters of hanger installation plan, and proceed to construct an automatically searching strategy for determination of the plan for self-anchored suspension bridge with 3D curved cables. The method yields the rational plans and significant process information by automatically updating from ideal tentative construction steps with a divided tension optimized strategy. To achieve high computational efficiency, the construction steps are implemented by proposing an indiscrimination coordinate rod model (ICRM) to model the bridge structure as well as coordinate iteration-based methods (CIMs) to identify the equilibrium of ICRM. On the basis, detailed NFEM is avoided and the design efficiency is greatly improved for the determination of the plan. The framework of the proposed method is detailed in Section 2. The method introduces ICRM in Section 3, which represents the equilibrium associated with the major deformation of the entire bridge by a simplified model composed of various specific rods. To identify the equilibrium of ICRM in construction, an efficient algorithm is then proposed in Section 4 for construction steps in terms of considering actual stretching forms. Then, a modification sub-step method is finally proposed to realize an automatically searching strategy in Section 5. The accuracy and efficiency of the proposed method are demonstrated by comparison case studies, field test verification and application discussion in a real-scale bridge in Section 6.

2. Proposed method

For self-anchored suspension bridge with 3D curved cables, it is impossible to observe all the mechanical parameters of the structure in construction site. Although the stress in critical positions of deck and tower are checked from time to time to ensure safety, they may not influence the installation plan as sensitively as the hanger tensions, deformations of cable system and movements of some key points. These parameters are always taken as the major control index in installation monitoring. A uniform stretching process generally satisfies the requirements of safety, but the major control index should be monitored to fulfil both design parameters and site limitations. Here efficient methods to get major observed parameters of construction steps are firstly required.

Thus, the proposed method is developed from a new understanding of the structure. Fig. 1 shows the structural features in two states. If all deformations of this type of structure are complex, then a key deformation that functions as the main cooperative system and another that functions as a subordinate system should be established. The tower and deck mainly introduce axial compressive deformations and the main cable causes axial tensile deformations. Thus, an independent equilibrium system that comprises axial deformations that serve important functions and are closely related to the unstrained lengths of members can be abstracted and analyzed separately using rods and additional boundaries. The method aims to describe the properties of this system by a specific model and determine its equilibrium in construction through the proposed linear coordinate iteration-based algorithms. In this manner, NFEM can be avoided because the large deformation of the cable system is included in the axial deformation of this system. Other non-axial deformations, mostly existing in framed structures identified as small deformations, can be solved by analytical theories to iteratively modify the lateral boundaries. The entire analytical process is referred to as the ICRM method.

The ICRM method in this study comprises a key function model (ICRM) and two correlated CIMs. The algorithms include the method for the general construction step (CIM-CS) considering actual stretching forms, and the method based on which automatically searching strategies can be realized for determining a hanger installation plan (modification sub-step method, CIM-MSM).

3. Specific rod model

ICRM involves a specific simplified model composed of rods, the real-time equivalent axial stiffness of beam–column rods, and the iterative modification of the *X*-boundary of the tower rods.

3.1. Model of ICRM

ICRM is composed of rods. "Indiscrimination" in ICRM refers to being uniformly described by rods with different properties and being stably solved in a fixed mode. "Coordinate rods" are those that directly locate the coordinates though the CIMs. In fact, the elastic catenary element may not achieve the highest precision because the main cable usually exhibits cable flexibility and beam rigidity [30] in reality. Compared with this type of element, the truss (rod) element is as precise but more economic and attractive for construction step analysis as long as it is applied rationally. Therefore, the rod element is feasible to abstract the major deformations of the entire bridge. Below are the main preconditions and assumptions for ICRM.

(1) For the beam–column rods, the actual bending moments are utilized to modify axial stiffness considering the effects of bowing [28,31]; the modified result is referred to as the "axial tangent stiffness" (ATS). The transverse deflection of the deck can be neglected, and the actual location of the camber is considered in the eccentric bending moments for ATS modification.
(2) The sag effects [32] on the main cable rods that are properly discretized are neglected. Element division may influence the results in extreme cases but is not discussed in this study.
(3) The tension effects on the main cable rods are neglected.
(4) Hanger tensions are external forces in ICRM but considering both the unstrained lengths of the hangers and the actual positions of the anchorage points. Particularly, the *X*-axis positions of the anchorage points vary with the deformation of the ICRM.
(5) The effective supporting of the falsework is approximately situated on positions of crossbeams.