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A simplified structural mechanics model for cable-truss footbridges and its implications for preliminary design

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ABSTRACT

Compared with traditional suspension footbridges, the cable-truss footbridge is always easier to satisfy structure deformation requirements under small dead-load-to-live-load ratio condition, and it enjoys surging popularity in western China. In this type of bridges, the deck system is designed as a pure local load-bearing member, and the inverse pre-tensioned deck cable system is set up to form a tension–tension mechanical system. To better understand its structural performance, a simplified structural mechanics model for cable-truss footbridges is proposed, and the analytical formulations for deformation and internal forces of the bridge under entire span live load as well as semi-span live load have been derived. The reliability and accuracy of the proposed model have been validated in a comparison study with the finite element analysis. Furthermore, a series of qualitative and quantitative parametric studies have been conducted, which reveal that the cable-truss bridges have several novel structural characteristics that differ from that of traditional suspension bridges. Finally, the affordability range of cable-truss bridges is also discussed by using material usage analysis.

1. Introduction

With emergence of new materials, advanced structural engineering technology, and demands of larger spans in bridge and building structures in modern society, more and more cable-supported structures are being built due to their light weight, high strength, ease of construction, and aesthetic appearance. In recent years, many novel structure types of cable supported footbridges have been built or designed, such as ribbon footbridges, tensegrity-based footbridges, and suspension footbridges with a reverse profiled pre-tensioned cable e.g. [12,18], and [22]. However, due to its small dead-load-to-live-load ratio, no matter what geometric configuration of the bridge is, large span cable supported footbridge always suffers the shortcomings due to its intrinsic characteristics being slender and flexible, this makes it prone to vibration induced by functional activities or wind loads. Accordingly, pedestrian or wind-induced vibrations have become a focal point in the cable-supported footbridge design and research e.g. [27,6,23], and [15]. Obviously, increasing suspension footbridge's deck or girder stiffness is one of the best ways to improve the structure's load bearing capacity. However, this approach will increase the overall dead-load-to-live-load ratio, and hence it is often expensive. Therefore instead of increasing footbridge's deck/girder stiffness, researchers have attempted to enhance the load bearing capacity as well as dynamic performance of the bridge by modifying the hanger system, such as adding stay cables, and so on, e.g. [24,13,8]. Among of them, an effective approach to enhance the suspension bridge's overall stiffness and to control the bridge's deformation amplitude under external loads is to add an inverse pre-tensioned cable below the bridge deck to form a cable-truss structure (see Fig. 1(a) and (b)), and this technique was originated from the cable-truss roof construction. The cable-truss footbridge is composed of a bi-concave cable and tension hangers, whereas conventional cable-truss structures are usually designed to be composed of a bi-convex cable and compression struts. Compared to traditional suspension bridges, the deck system in a cable-truss footbridge can be designed solely as a local load-bearing member, whose vertical stiffness is very small so that it can be neglected in the mechanical analysis; the prestressed reverse profiled cable is set up to share the load and to enhance the overall stiffness of the bridge. This form of structure is also called cable-truss beam developed by Swedish engineer, David Jawerth in the 1960s (see: Buchholdt [2]), and then this structural system was late applied to roofs (Fig. 1c) and footbridges by other engineers such as Majowiecki [21], Schlaich and Englesmann [11], and Strasky [12] and

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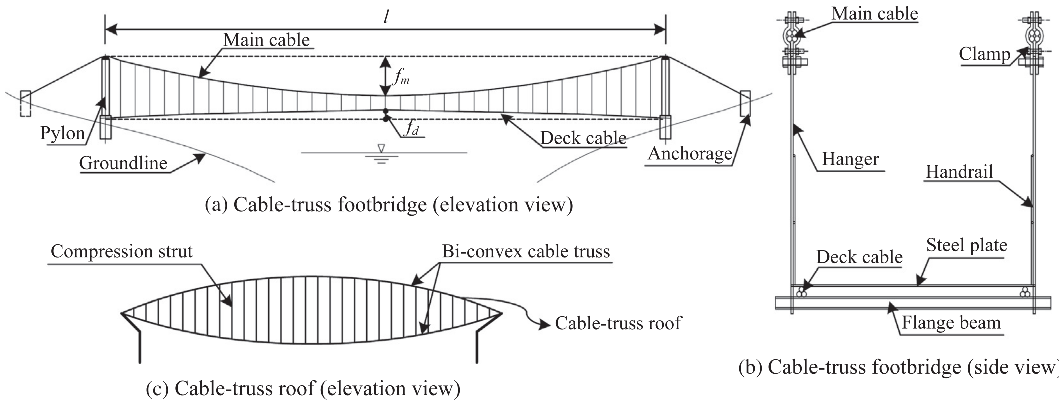

Fig. 1. Cable-truss structures.

others. Zetlin's Municipal Auditorium in Utica, New York was the first cable-truss structure, and comprehensive analytical treatments of cable-truss structures used in buildings were given by Schleyer and Møllmann (see: Irvine [9]), and then some celebrated roof structures including David L. Lawrence Convention Center in Pittsburgh, PA, Chonju World Cup Stadium in Korea, and an exhibition hall for the Hanover Fair [14] also adopted similar structural design. After that, reverse profiled cables have been extensively used to enhance the lateral stiffness of suspension bridges, such as the M-bridge built in 1999 [28].

Huang et al. [19,20] proposed a shallow suspension footbridge with reverse profiled pre-tensioned cables, and conducted a series of studies examining the deformation and vibration characteristics of this type of footbridge by using finite element method. To reduce cable's shape change under the action of non-uniform loads, Goremikins et al. [30] replaced the main cable by a cable truss beam with cambered top and bottom chords and inclined web element, where all truss elements are tensioned, and subsequently their vertical displacements are reduced. In general, the application and research of cable-truss structure on bridge engineering lags relatively behind to those of roof structures.

Cable-truss structure is a complex structural form with strong nonlinearity. As the development of finite element method, nonlinear finite element method has been extensively used to analyze mechanical strength and performance of cable-truss structures [17,16,30]. However, in preliminary/conceptual designs, a relatively simple analytical method can provide a reasonable and quick estimate for structural engineers in analysis and design of cable-truss bridges. As mentioned above, comprehensive analytical treatments of cable-truss structures used in buildings were given by Schleyer and Møllmann [9]. They neglected all the second-order terms in the differential equations of both cable equilibrium and compatibility conditions to obtain a linearized approximation theory to analyze static responses of cable-truss structures under external loads. This method also had been adopted in the some later works, e.g., Baron and Venkatesan [5], Urelius and Fowler [29] and Buchholdt [2]. Monforton and El-Hakim [7] used the energy method to analyze pin-ended cable-truss structures. In this work, both geometric and material nonlinearities are directly incorporated within the structural mechanics formulation. Recently, Kmet and Kokorudova [25,26] have proposed a more sophisticated structural mechanics model for cable-truss structures. They kept the high-order terms neglected in the linearized approximation theory mentioned above, and considered a suspended biconvex and biconcave cable-truss with unmovable, movable, or elastic yielding supports subjected to vertical distributed loads applied over the entire or semi span. The proposed mathematical model for cable-truss structure is derived on the basis of initial cable shape and the structure response that was obtained from the load equilibrium equations and cable compatibility equations. And all of the methods mentioned above assumed that the hangers are arranged vertically and inextensible.

In this paper, a novel structural mechanics model for cable-truss bridges under either entire or semi span loading is proposed. Different from the previous cable-truss bridge models, whose solutions require the load conditions of two different cases, the structure's deformed configuration is determined at first in terms of mid-span sag and external load parameters, and then the cable compatibility equations are used to acquire the mid-span sag. By this way, the derivations are greatly simplified. During the derivations, some approximations or assumptions are being made, which are similar to that of the existing models. Even though, for long span footbridge, the pedestrian or wind induced vertical or transverse vibration are important issues, and they have attracted the much attention of many researchers e.g. Taylor and Vezza [10], Fiore and Monaco [1], Ingólfsson and Georgakis [4]. However, these factors are not considered in the proposed model, because the objective of this paper is to build a simple model for preliminary/conceptual static design. The reliability and accuracy of the proposed model is validated through a comparison study with the nonlinear finite element method. Besides these studies, a systematic parameter analysis has been performed to investigate the stiffness relationship between the main cable and deck cable according to different dead or live load conditions. The optimal analysis was also conducted to determine the affordability range for cable-truss bridges, which is depended on the load conditions and material strength.

2. Mechanics model for single cable structures

First, it is necessary to establish a single cable statics model, which can serve as the basis of the cable-truss bridge model. An exact analysis of simply suspended cable problems is somewhat restricted because the solution methods are cumbersome. Simplifications can be made when the profile of the cable is flat, and this often corresponds to situations in which cables with relatively low sag are used for structural purposes. The approximation method based on parabola theory provides explicit and consistent methods for finding the static response to applied loads that are accurate to the third order of small quantities [9]. All of the derivations in this paper are based on structural mechanics and analytic geometry instead of energy approaches. The following assumptions are made for the derivation of the mathematical governing equations: