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Multi-objective optimization of polyester-rope and steel-rope suspended footbridges

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ABSTRACT

Historically, suspended footbridges have been built from ropes (i.e., cables) constructed of a variety of materials including iron and natural fibers. However, contemporary suspended footbridges are typically constructed with steel rope. One exception, a 64 m span polyester-rope footbridge completed in 2013, demonstrates the potential for alternative rope materials in contemporary footbridge design and construction. The first goal of this paper is to support the idea that polyester rope has promise in future footbridge applications by comparing minimum rope volume and self-weight results for polyester-rope and steel-rope footbridges with spans ranging from 15 to 64 m in two multi-objective optimization problems. In both problems the competitive objective functions are span which is maximized and rope volume which is minimized. The results are minimum volume systems for spans in the defined range. Minimizing volume reduces rope cost and eases material transport and handling. To provide an alternative measure of rope quantity, volume results are scaled to find the equivalent self-weights. This study focuses on in-plane structural behavior and investigates two-dimensional rope systems with or without prestress and with or without under-deck stays. A combination of static and natural frequency constraints is considered in the optimization problems. The second goal of this paper is to describe the novel methodology developed to evaluate these optimization problems. This methodology combines a non-dominated sorting genetic algorithm for searching the design space with dynamic relaxation and eigenanalysis algorithms for the structural analysis. Results indicate that polyester-rope systems have higher volumes, but lower self-weights than steel-rope systems. This observation supports the premise that polyester-rope footbridges are potential alternatives to steel-rope footbridges. The presented methodology can be adapted to evaluate how other unconventional materials compare to more conventional counterparts that are well established in bridge applications.

1. Introduction

Suspended footbridges are commonly built to improve access at sites that are not easily spanned with simple beams [1] or trusses. While the term “suspension” is sometimes used interchangeably with “suspended”, in this paper, a suspended bridge is defined as having a deck that sits directly on draped under-deck ropes (i.e., under-deck cables) and may have additional draped ropes that also serve as handrails (i.e., hand ropes). In contrast, a suspension bridge has a deck that is hung from one or more draped ropes that pass over towers. A suspended bridge’s hand ropes also span between towers. These towers are shorter than those of suspension bridges because of the low sag-to-span ratios of the hand ropes.

The mechanics of the major feature of a suspended bridge, the hanging rope, has been well studied. Irvine [2] provides a historic discussion on the development of the static catenary equations, presents an approximate theory for static calculations performed on flat sag (sag-to-span ratios less than 1:8) ropes, and describes the linear theory of free vibration of ropes. Gimsing and Georgakis [3] present static and dynamic equations for a single cable and describe how to analyze suspension and cable-stayed systems. The suspension system is similar to a suspended footbridge whose ropes are not prestressed. Suspended bridges whose ropes are prestressed may be referred to as stress ribbons. These structures may consist of a prestressed concrete deck that provides greater stiffness than the ropes on their own [4]. An alternative

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way to stiffen a suspended rope is to provide a prestressed supplemental rope with opposite curvature that acts with the suspended rope to form a rope truss. The trusses can be biconcave or biconvex where the upper and lower truss chords are connected by elements subject to tension in the former and compression in the latter [2]. Various biconcave truss footbridge configurations have been proposed and evaluated statically [5,6] and dynamically [7,8]. Discrete rope stays (i.e., guys) may be used instead of a rope truss to stiffen a bridge. Cable stays may be provided above the deck in lieu of a suspended rope and serve as the principal load carrying members in a cable-stayed system [9]. A prominent example of a hybrid cable-stayed/suspension system [3] in which both suspension ropes and above-deck stays in addition to a stiffening truss are utilized is John A. Roebling's Brooklyn Bridge [10]. In another Roebling structure, the Niagara Railroad Bridge, the suspension ropes, above-deck stays, and stiffening truss are supplemented with under-deck stays to stiffen against wind effects [11].

Historic examples of suspended footbridges date back to at least the 15th century and include Tibetan and Bhutanese iron chain [12] and Incan natural fiber-rope [13] bridges. Steel-rope suspended bridges are currently built worldwide by humanitarian groups such as Helvetas [14] and Bridges to Prosperity [1]. Few contemporary suspended footbridges have been built with rope material other than steel. Two temporary, laboratory-scale prototypes include a 13 m span stress ribbon that has carbon fiber reinforced polymer (CFRP) ropes and a concrete deck [15] and a 13.7 m polyester-rope truss [16]. One key larger scale example is a 64 m span, 1.02 m wide polyester-rope suspended footbridge with a non-composite wood deck completed in 2013 in Ait Bayoud, Morocco (Fig. 1). In addition to improving the local infrastructure, the bridge was built to demonstrate that polyester rope, which is used in large-scale marine applications such as offshore mooring [17], but is rarely utilized in civil engineering applications, has potential as an alternative to steel rope for suspended footbridges.

The first goal of this paper is to strengthen the idea that polyester rope has promise in suspended footbridge applications by comparing minimum rope volume and self-weight requirements for polyester-rope and steel-rope bridges for spans up to 64 m. Two-dimensional polyester-rope and steel-rope suspended systems (with or without prestress and unstayed or stayed from below the deck) are analyzed in a set of multi-objective optimization problems. The second goal of this paper is to present the novel methodology developed for the optimization process. This methodology combines a non-dominated sorting genetic algorithm with nonlinear elastic static and natural frequency computations that utilize dynamic relaxation and eigenanalysis algorithms. In each optimization problem, two objective functions are considered. The first objective function, the span, is maximized while the second objective function, the volume of the unstressed rope system, is minimized. Maximizing span in a multi-objective optimization provides solutions across a range of spans. This enables conclusions to be drawn about what parameters may be critical at different spans. Similar results could be obtained by repeating for each span of interest, a single objective optimization, where volume is minimized. Minimizing volume is important to reduce the quantity and the cost of rope. Since polyester and steel have different densities, self-weight can be scaled from the volume results to provide an alternative measure of rope quantity. Minimization of a suspended rope's self-weight has been considered in multi-objective optimization problems where the second objective function, the lowest natural frequency was maximized [18,19]. The minimization of a suspended rope's volume and maximization of the lowest natural frequency has been studied for the specific case of a polyester-rope suspended footbridge and its associated design variables and static constraints [20]. That case study also accounted for robustness in the form of uncertainties on the model inputs. In the present study, the vertical natural frequency is included as a constraint rather than as an objective function. Other constraints include static stress and walking slope criteria.

The remainder of this paper is organized as follows. First, the features of the structural models are described (Section 2). These features include model configurations, rope properties, and design loads. Next, the multi-objective optimization problems are presented (Section 3). The general problem formulation is defined and then the objective functions, constraints, and design variables for the different problems and cases are discussed. Then, the optimization methodology is described (Section 4). Finally, the results are presented and discussed (Section 5) and the major conclusions are described (Section 6).

2. Structural model features

2.1. Model configurations

In this study, 1 m wide, three-dimensional suspended rope systems with and without under-deck stays are reduced to two-dimensional models. This reduction is achieved by grouping together all elements occurring at the same elevation. By only considering two instead of three dimensions, this study demonstrates how the optimization methodology handles both static and dynamic constraints related to in-plane behavior. Using this methodology a future study can consider a three dimensional structure and its associated out-of-plane structural behavior. This may include capturing the bridge's behavior when subjected to pedestrian-induced lateral vibration issues such as crowd synchronization with the bridge response [21,22].

Fig. 2a–c shows detailed configurations that consist of components such as suspended hand and under-deck ropes, suspenders, backstays, and under-deck stays (Fig. 2b and c). Simplifications to the configurations in Fig. 2a–c appear in Fig. 2d–f. The configurations in Fig. 2d–f have a single suspended rope and no suspenders or backstays. The extremes among these configurations, the low-stiffness and high-stiffness configurations in Fig. 2d and f,

Fig. 1. Polyester-rope suspended footbridge (Ait Bayoud, Morocco, 2013) showing hand and under-deck ropes, as well as two short towers.