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Static and dynamic analyses of a suspension bridge with three-dimensionally curved main cables using a continuum model

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ABSTRACT

In this paper, a continuum model is proposed for static and dynamic analyses of a three-span suspension bridge with three-dimensionally curved main cables. To obtain equations of motion for this model, coupled differential equations are derived for vertical displacements of a main cable and a girder as well as lateral displacements of a main cable subjected to external loads. A compatibility equation of a three-dimensionally curved cable is also derived. Utilizing the Galerkin method, the equations of motion are obtained in matrix form. A case study bridge is used to verify the continuum model against a finite element model. Verification results show that, for distributed static loads on the girder and temperature changes in the main cable and the hangers and for dynamic moving loads on the girder, the continuum model can accurately determine static and dynamic responses, namely displacements, velocities, accelerations, bending moments, and shear forces of the girder and additional horizontal forces in the main cable.

1. Introduction

A suspension bridge can be analyzed by two types of models: finite element models and continuum models. Finite element models have many hundreds of finite elements which are used to discretize members such as a cable and a girder in the bridge. These finite element models have high accuracy and generality, but require time-consuming modelling procedures including initial equilibrium state analysis and require high computational resources because of their many thousands of degrees of freedom. In contrast, continuum models based on the deflection theory consider each span of the bridge as a continuum and do not need discretization which is used in finite element models. These continuum models do not require the initial analysis and require much fewer degrees of freedom because of their simple governing equations. Therefore, these models can be useful during preliminary analysis to determine bridge properties from extensive parametric analyses and to independently verify complex finite element models.

Continuum models have been widely studied by many researchers for free vertical or torsional analysis [1–11] and for static analysis [12–21] of suspension bridges. In addition, continuum models have been adopted for the analysis of suspension bridges under dynamic loads such as moving loads [22–26], seismic loads [27,28], and combined loads [29–32].

Main cables in suspension bridges generally are of two-dimensional shape, comprising curves in vertical planes. However, they sometimes are of three-dimensional shape, with curves in both vertical and horizontal planes (Fig. 1). For example, the San Francisco Bay Bridge in the United States and the Yeongjong Bridge in Korea have three-dimensionally curved main cables. Suspension bridges with three-dimensionally curved main cables are considered more beautiful and have greater lateral stability [33–35]. Studies on this bridge type have typically focused on initial equilibrium state analysis [33,34,36] or construction stage analysis [37,38]. However, because of its structural complexity, finite element models for this bridge type require a more complicated modelling procedure and greater computational resources relative to conventional bridges with two-dimensional main cables [33,34,36–38]. Therefore, it is necessary to develop a continuum model for a bridge with three-dimensionally curved main cables.

In this paper, a continuum model is proposed for static and dynamic analyses of a three-span earth-anchored suspension bridge with three-dimensionally curved main cables. To obtain equations of motion for this model that can consider extensible hangers, coupled differential equations are derived for vertical displacements of a main cable and a girder as well as lateral displacements of a main cable subjected to external loads. A compatibility equation for a three-dimensionally curved cable is also derived. Utilizing the Galerkin method, the equations of motion are obtained in matrix form. A case study bridge is used to verify the continuum model against a finite element model.

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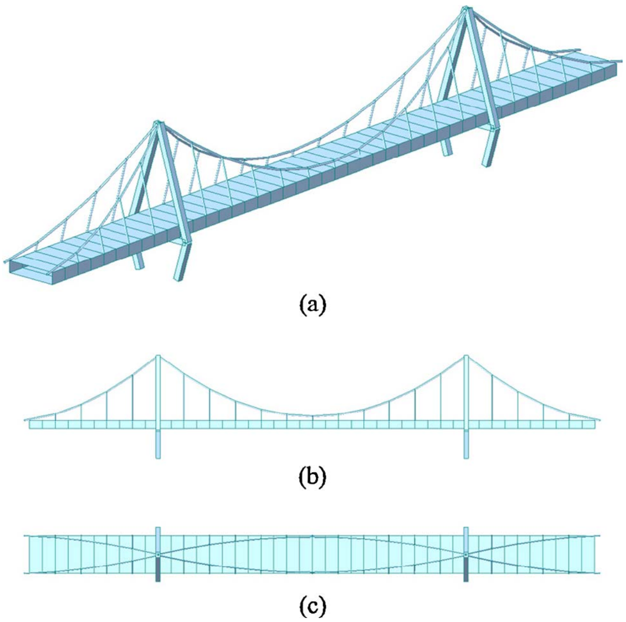

Fig. 1. Suspension bridge with three-dimensionally curved main cables: (a) three-dimensional, (b) front, and (c) top views.

2. Single-span suspended girder with three-dimensional curved main cables

2.1. Basic assumptions and differential equations

Fig. 2(a) shows a single-span suspended girder with three-dimensionally curved main cables and inclined hangers, where x, y, and z are the coordinates for longitudinal, horizontal, and vertical axes, respectively. A continuum model for this cable–girder system proposed in this paper is based on the following eight assumptions. (1) The dead load is uniform and carried only by the cable; thus, the girder has no vertical displacement under the dead load. (2) The cable shape is parabolic under the uniform dead load. (3) The hangers are continuously distributed along the girder. (4) The hangers are initially parallel to the y–z plane and remain parallel during vibration. (5) The displacements of the cable and the girder are small so that the additional horizontal force in the cable caused by these displacements is small in comparison with the horizontal force under the dead load. (6) The hangers are massless and extensible. (7) Vertical external loads are applied to the girder's centroid and to the two cables symmetrically with respect to the x–z plane. (8) The mass of the cable is small compared to that of the girder.

The first five assumptions above are usually adopted in conventional continuum models, although Arena and Lacarbonara [39] excluded the second, forth, and fifth assumptions in their model. The fifth assumption ensures that the continuum model has linear behaviors. The description of the extensible hangers in the sixth assumption allows for elongations of the hangers between the cable and the girder so that the displacement of the girder is not equal to that of the cable. The seventh assumption leads the girder to only have vertical displacements and also leads the displacements of the two cables to be symmetric with respect to the x–z plane of the bridge. The eighth assumption ensures that the cable and the hangers remain in an identical inclined plane and thus ensures that the angle between the horizontal plane and the inclined plane is constant along the bridge.

Fig. 2(b) shows cross-sectional views of the initial and deformed shapes of the cable–girder system under consideration. Since the seventh assumption leads to symmetric displacements of the cables with respect to the x–z plane, only half of the section is considered. In Fig. 2(b), o is the inclined axis in the plane of the cable and the hangers; w_c and w_g are the vertical displacements of the cable and girder, respectively; v_c is the lateral displacement of the cable; l_{hz}, l_{hy}, and l_{ho} are the vertical, horizontal, and inclined lengths of the hangers; and θ and θ' are the slope angles of the hangers in the initial and deformed shapes. The angle θ also represents the angle between the horizontal plane and the inclined plane of the cable and the hangers, which is assumed to be constant along the bridge.

Fig. 3 shows the load conditions of the cable, hangers, and girder in the vertical and horizontal planes. In Fig. 3, m_c and m_g are the uniform masses of the cable and the girder per unit length along the x -axis, respectively; p_c and p_g are the external loads on the cable and the girder; g is the gravitational acceleration; E_c and A_c are the elastic modulus and the cross-sectional area of the cable; E_h and A_h are the elastic modulus and the cross-sectional area of the hangers; E_g and I_g are the elastic modulus and the moment of inertia of the girder section; L is the

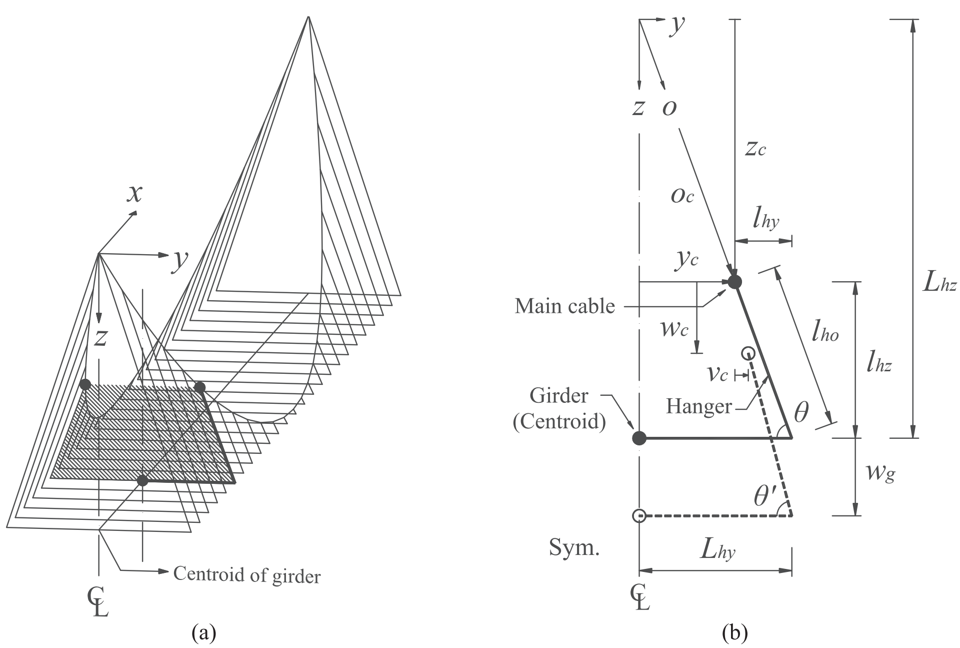

Fig. 2. (a) Single-span suspended girder with three-dimensionally curved main cables and inclined hangers, and (b) cross-sectional view of its initial and deformed shapes.

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