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A new steel structural system of a suspension pedestrian bridge

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Abstract

The paper deals with a new structural system of pedestrian steel bridge consisting of carrying suspension members made of stiff (in bending) rolled or welded sections and a flexible cylindrical deck. Structural behaviour of such a suspension member subjected to unsymmetrical live loading has been discussed on a basis of kinematic conditions. Ways of stabilization of kinematic displacements have been under consideration. Effects of bending stiffness and geometrical non-linearity of the suspension structure are taken into account. Analytical expressions for the analysis of the flexible cylindrical deck have been proposed. In an alternative concrete deck, a layered model has been applied for the stress and strain analysis.

Keywords: Suspension pedestrian bridge; Steel cable; Kinematic displacement; Stiff suspension steel member; Deck; Stress–strain analysis

1. Introduction

Due to material efficiency, lightness and aesthetics reasons, suspension structures are widely used not only in roofs of buildings, but also in pedestrian bridges [1–9]. For many years, the so-called catenary structures have been successfully employed in suspension pedestrian bridges. High strength cables or steel sheets serve as the main carrying members in such bridges [9–13]. One of the most serious drawbacks of suspension structures is their excessive deformations when subjected to asymmetric and local loads. It is a common practice to use heavy concrete decks in order to reduce displacements of a kinematic nature [9,12,13]. A sag f_0 of the main carrying cable is relatively small ($f_0 \cong l/70 \div l/80$), thus resulting in excessive tensile forces in the cable and stronger anchoring foundations [12–17].

A completely flexible suspension cable is a pure theoretical concept, as in real structures it has a certain bending stiffness [3, 11,18,19]. It is obvious that such structures carry loads not only due to tension, but also due to bending response. Some structural solutions of suspension roofs are known [3,20, 21] where stiff (in bending) suspension members are used in order to reduce displacements caused by asymmetric and local loads. Use of such carrying members made of rolled or welded sections permits effective stabilization of the primary shape of the whole structure avoiding heavy and often rather expensive concrete decks. Although two-hinge members is a common practice in the design of the suspension structures [3,5], alternative three-hinge structures [20,21] have some advantages: internal forces are reduced due to inevitable displacements of the supports.

As an alternative to concrete decks, various new structural solutions [22], including flexible cylindrical steel decks [23, 24] known from the design of roofs and floors in buildings and decks in transport bridges, can be used in suspension pedestrian bridges. The weight of such decks is several times lower compared to the traditional profiled steel sheeting or orthogonal steel plates [23,24].

This paper proposes a new structural system of pedestrian steel bridge consisting of carrying suspension members made of stiff (in bending) rolled or welded sections and a flexible cylindrical deck. Structural behaviour and ways of stabilization of kinematic displacements of a cable subjected to unsymmetrical live loading has been discussed. Analytical expressions for the analysis of a stiff (in bending) suspension structure and the flexible cylindrical deck have been proposed. In an alternative concrete deck, a layered model has been applied for the stress and strain analysis. The effectiveness of

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Nomenclature

H_1	Thrusting (tensile) force of stiff suspension members
H_p	Thrusting (tensile) force of the steel sheet
$M_1(x_1)$	Bending moment due to external load
P	Initial pre-stressing force
d_n	Distance from the initial pre-stressing force to the top edge
f_{k1}	Kinematic sag of the cable in the middle span
f_0	Initial sag of the cable in the middle span
f_{p0}	Initial sag of the steel sheet
f_{l0}	Initial sag of the left part of the structure
kl	Flexibility parameter of stiff suspension members
$m_1(x_1)$	Bending moment of stiff suspension members
t_p	Thickness of the steel sheet
$w_{\max}$	Maximal kinematic displacement
$w_1(x_1)$	Displacement of stiff suspension members
$w_{\text{fic}}(x_1)$	Fictitious displacement of stiff suspension members
$z_1(x_1)$	Primary shape of the stiff inclined member
Δf_k	Kinematic displacement in the middle span
$\Delta f_{\text{fic},l}$	Fictitious displacement of the left part of the structure
Δf_p	Displacement of the steel sheet
$\Psi(kl_1)$	Function assessing the bending stiffness of the member
μ	Poisson's ratio
γ	Ratio of asymmetric and symmetric load intensities

the proposed structural systems of the suspension bridge has been discussed from the technical and economic point of view.

2. Kinematic displacements and their stabilization in asymmetrically loaded cable

2.1. Kinematic displacements

Cable is the main carrying structural member in suspension pedestrian bridges. Consider a suspension cable shown in Fig. 1 subjected to uniformly distributed per cable span load q. Such loading induces elastic, but not kinematic, displacements of the cable shown by a solid line. The primary shape of the cable is described by the equation of a quadratic parabola.

An additional asymmetrical load (say a uniformly distributed load p applied on the left half of the span as shown in Fig. 1) causes significant displacements inducing the change of the primary shape. Under the assumption of infinite axial stiffness of the cable, change of the shape is caused by kinematic displacements only [25]. Under consideration of both symmetrical and asymmetrical load, the deformed cable axis has to be defined separately for the left and right sides:

$$z_{lk}(x) = \frac{f_{k1}}{(1+0.5\gamma)} \cdot \left[\left(\frac{4x}{l} - \frac{4x^2}{l^2}\right) + \gamma\left(\frac{3x}{l} - \frac{4x^2}{l^2}\right)\right], \quad \text{when } x \le 0.5l \tag{1}$$

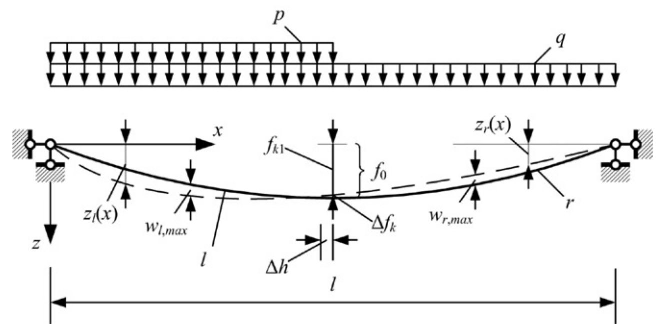

Fig. 1. Deformed scheme of asymmetrically loaded cable.

$$z_{rk}(x) = \frac{f_{k1}}{(1+0.5\gamma)}\left[\left(\frac{4x}{l} - \frac{4x^2}{l^2}\right) + \gamma\left(\frac{x}{l} - 1\right)\right], \quad \text{when } 0.5l \le x \le l. \tag{2}$$

Here $\gamma = p/q$.

Analysis has shown that the kinematic sag of the cable in the middle span f_{k1} takes smaller values in respect to the initial sag f_0 meaning that the middle section due to asymmetrical loading moves upward. The kinematic displacement is calculated by the formula:

$$\Delta f_k = -f_0\left(1 - \frac{1+0.5\gamma}{\xi}\right). \tag{3}$$

Here $\xi = \sqrt{1+\gamma+5\gamma^2/16}$.

The maximal kinematic displacement can be defined as:

$$w_{lk,\max}(x) = \frac{3}{4} f_0\left[\frac{(1+2\gamma/3)}{\xi} - 1\right]. \tag{4}$$

Analysis has shown that the above formula produces insignificant errors not exceeding 1.6% even for the cases when γ reaches 10 [25]. Vertical kinematic displacements w_{rk} on the right side of the cable are directed upward. Similarly, displacements of the right side of the cable are to be calculated by the formula:

$$w_{rk,\max}(x) = \frac{3}{4} f_0\left[\left(\frac{1}{\xi} - 1\right) + \frac{\gamma}{3\xi}\right]. \tag{5}$$

Analysis of Eqs. (4) and (5) has shown that the kinematic displacements on the right side of the cable in absolute value are larger than the ones on the left side ($w_{rk,\max} > w_{lk,\max}$). It can be explained by the fact that the midpoint displacement is negative [25–27]. The difference between the maximal displacements of the left and the right side of the cable ranges from 28% to 86% for different load ratio γ values.

2.2. Stabilization of kinematic displacements

The stiffness condition $w_{\max} \le w_{\lim}$ is of particular importance in the design of suspension pedestrian bridges. Asymmetrical load induces significant vertical displacements of a kinematic nature. According to Eqs. (4) and (5), maximal kinematic displacements are dependent on the load ratio γ and the initial cable sag f_0. Various techniques are available for stabilization (or reduction) of kinematic cable displacements.