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Predicting the flutter speed of a pedestrian suspension bridge through examination of laboratory experimental errors

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ABSTRACT

The paper investigates experimental error propagation and its effects on critical flutter speeds of pedestrian suspension bridges using three different experimental data sets: pressure coefficients, aerodynamic static forces and flutter derivatives. The three data sets are obtained from section model measurements in three distinct laboratories. Data sets are used to study three different geometries of pedestrian suspension bridges. Critical flutter speed is estimated using finite-element nonlinear analysis, numerical 2-DOF generalized deck model and 3-DOF full-bridge model. Flutter probability, contaminated by various experimental error sources, is examined. Experimental data sets are synthetically expanded to obtain two population sets of deck wind loads with 30 and $5 \cdot 10^5$ realizations, respectively. The first set is obtained using Monte-Carlo simulation approach, whereas the second one is determined using Polynomial chaos expansion theory and a basis of Hermite polynomials. The numerically-determined probability density functions are compared against empirical probability histograms (*pdfs*) by Kolmogorov-Smirnov tests.

1. Introduction

Conurbations are more and more affected by traffic pollution, leading to a policy trend that promotes public transportation and pedestrian and bicycle pathways. Many governmental master plans contemplate new "green roads" around downtowns, across rivers or highways. The goal is to create a comfortable alternative way to get around town. Pedestrian bridges play a fundamental role as part of this trend because they are an efficient way to connect different neighborhoods of a large city.

One of the critical aspects of pedestrian bridges is their impact on the natural environment due to the presence of either pillars, substructures or support structures. River crossings are especially critical because, in order to reduce the bridge span, pillars are often located in the waterway. This aspect often causes controversies between designers and ecologists regarding preservation of the natural ecosystem. Examples of pedestrian bridges with intermediate supports are: the London Millennium Footbridge (2000) that has a total length equal to 325 m and a central span length equal to 144 m, the Puente de La Mujer (2001), Buenos Aires, Argentina with a total length equal to 170 m but with its longest span equal to 102.5 m and the Goodwill Bridge, crossing the Brisbane River in Brisbane, Queensland, Australia, which has a total length of 450 m with its longest span equal to 102 m. Another recent example is the Sea Bridge on the Pescara River in Pescara, Italy [1]. This structure is the longest pedestrian-and-bicycle bridge in Italy and one of the longest in Europe. Its total length is 466 m and the length of the longest central span is 172 m.

Pedestrian bridges with increasing spans require larger sub-structures; this need leads to higher costs. The deck section height and width are influenced by span length. Suspension bridges are commonly used for pedestrian bridges to obtain long spans and minimize the risk of environmental interferences. This solution, using a typical scheme such as the one illustrated in Fig. 1a, permits structural construction with a single large span. In this standard configuration, the pillars are used in conjunction with parabolic cables for the main span and "back" stay-cables for the lateral spans [2,3]. However, this geometrical configuration may be invasive near rivers since the use of multiple spans could negatively affect integration of the bridge with the urban context. For this reason, the solution illustrated in Fig. 1b may be more successful for pedestrian bridges. This solution has inclined pillars to

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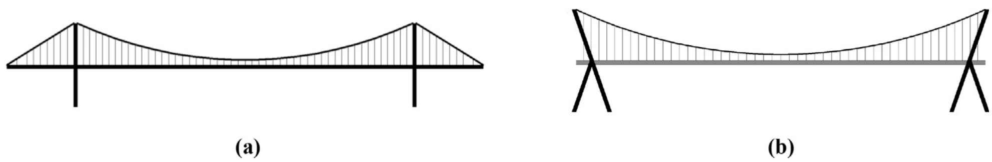

Fig. 1. Suspension bridge: reference design (a), modified design (b).

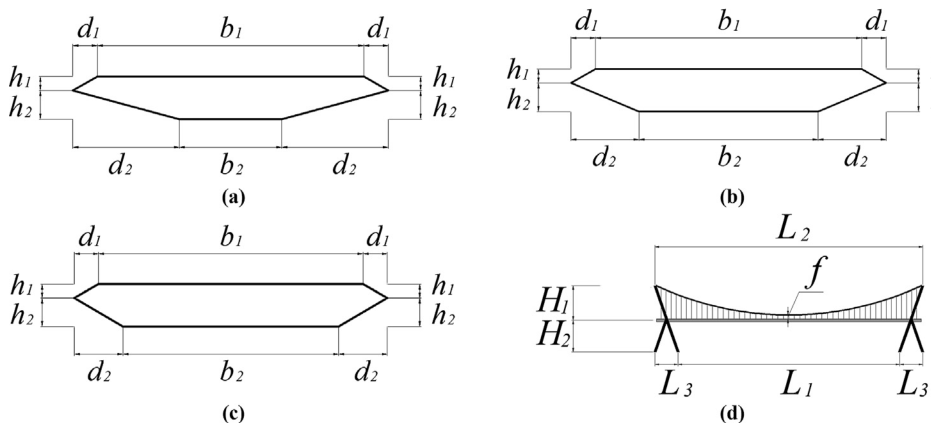

Fig. 2. Geometrical parameters: MOD1 (a), MOD2 (b), MOD3 (c), Pedestrian bridge outline (d).

Table 1
Main geometric properties of the full-scale deck girders and wind tunnel section models (S- and P-tests).

		h_1	h_2	d_1	b_1	d_2	b_2
Full scale	MOD1	$0.53 \cdot 10^3$	$1.11 \cdot 10^3$	$0.86 \cdot 10^3$	$10.25 \cdot 10^3$	$4.10 \cdot 10^3$	$3.94 \cdot 10^3$
	MOD2	$0.53 \cdot 10^3$	$1.11 \cdot 10^3$	$0.86 \cdot 10^3$	$10.25 \cdot 10^3$	$2.62 \cdot 10^3$	$6.77 \cdot 10^3$
	MOD3	$0.53 \cdot 10^3$	$1.11 \cdot 10^3$	$0.86 \cdot 10^3$	$10.25 \cdot 10^3$	$1.89 \cdot 10^3$	$8.36 \cdot 10^3$
Wind tunnel model							
S and P-tests	MOD1	13	27	21	250	100	96
	MOD2	13	27	21	250	64	165
	MOD3	13	27	21	250	46	204
D-tests	MOD1	–	–	–	–	–	–
	MOD2	7	14	11	127	32	84
	MOD3	–	–	–	–	–	–

Notes: all values are in mm; the definition of the quantities refers to Fig. 2.

counteract large internal tension forces originating from the main suspension cables through tower anchorages.

The lightness and slenderness of pedestrian suspension bridge decks are the cause of two main structural problems: resonance due to large lateral vibration, induced by walking pedestrians [4–15], and flutter instability induced by wind loads. Both aspects are extensively investigated in the literature. The latter aspect, in particular, has been comprehensively studied in wind engineering for large span vehicular suspension bridges; several studies have proposed models and methods for the reliability analysis of vehicular bridges sensitive to flutter instability.

A general overview on bridge flutter is presented, for example, in Zasso et al. [16], who examine the state of the art in the field of bridge aerodynamics, describing a number of procedures for evaluating not only flutter stability but also turbulence-induced buffeting response, and in Pourzeynail and Datta [17]. Two important examples of systematic approach for flutter reliability analysis are: the model proposed by Ge et al. [18], which is formulated as a limit state threshold-crossing problem and a numerical calculation approach to determine the probability of bridge failure due to flutter; and by Cheng et al. [19], who propose a reliability analysis method by combining the advantages of the response surface method, finite element method (FEM), first-order reliability method and the importance sampling method.

Bridge flutter instability is primarily investigated by studying the aerodynamics and aeroelastic behavior of the deck section [20,21]. In the technical literature this aspect is examined using appropriately scaled deck section models, tested in wind tunnel to estimate aerodynamic forces (Lift, Drag and Moment) both directly (force measurements) and indirectly (pressure measurements), and to evaluate the flutter (or Scanlan) derivatives of the deck section [22,23]. Static and dynamic experiments are often conducted to study bridge instability phenomena. For example, Argentini et al. [24] describe experimental and numerical analysis of the dynamic response of a cable-stayed bridge with a focus on vortex induced vibrations and buffeting effects; Diana et al. [25,26] present a comparison between wind tunnel tests conducted on a full-bridge aeroelastic model of the proposed suspension bridge over the Strait of Messina (Italy). Similarly, Argentini et al. [27] compare wind tunnel tests carried out on a full aeroelastic model with numerical results for the Izmit Bay Bridge (Turkey). Several other literature studies have considered issues related to flutter derivatives, mostly examining the dependence between flutter derivatives and deck section geometry. One representative example is the study by Scanlan et al. [28] that analytically derive the interrelations and approximate correspondences among flutter derivatives of a bridge deck, obtained from theoretical low-speed airfoil aeroelasticity. Another significant example is the study by Matsumoto et al. [29], which focuses on the influence of each flutter derivative on flutter instability, obtained by pressure measurements on the side surface of 2-D rectangular cylinders with B/D side ratios (B is the chord length, D the deck height) between 5 and 20 and examining 1DOF coupled heaving/torsional forced