Engineering Structures 147 (2017) 545–566

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Uncertainties in crowd dynamic loading of footbridges: A novel multi-scale model of pedestrian traffic

Luca Bruno [a,*], Alessandro Corbetta [b]

[a] Politecnico di Torino, Department of Architecture and Design, Viale Mattioli 39, I-10125 Torino, Italy
[b] Eindhoven University of Technology, Department of Applied Physics, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 29 August 2016
Revised 24 May 2017
Accepted 29 May 2017

Keywords:
Footbridges
Uncertainty
Crowd load
Incoming pedestrian statistics
Crossing pedestrian probabilistic model

ABSTRACT

The study of the probabilistic response of pedestrian-excited structures as well as their reliability analysis need to take into account the influence of a large number of uncertain parameters ascribed to structural characteristics, single pedestrian walking features and pedestrian traffic phenomena. Although pedestrian traffic is characterized by an intrinsic high variability and plays a key role in determining the pedestrian load, its probabilistic description remains scarce in literature. The present work aims at contributing to the probabilistic evaluation of the pedestrian traffic across footbridges. First, a categorized state of the art focused on sources of uncertainty is provided. Second, a new modeling framework for the probabilistic evaluation of pedestrian traffic is introduced in general and conceptual terms. The framework is conceived in analogy to the approach developed in another engineering field, i.e. wind engineering, on the basis of the phenomenological features of the pedestrian traffic. In order to put the framework in practice, each of its main modeling components is specified. We introduce a statistic approach to evaluate the incoming traffic and a microscopic traffic model to simulate the propagation along the footbridge of the uncertain pedestrian entrance. In order to prove its technical feasibility, the proposed framework is finally applied to an ensemble of real world crowd events and to two ideal footbridges with differently shaped walkway. As a final result, the pedestrian density along the footbridge is described as a random field in terms of its joint and unconditioned probability density functions and correlation lengths.

1. Introduction

The issues of human-induced loads and related mechanical performances at both serviceability and ultimate limit state has become one of the leading research topic in structural engineering during the last decade, due to the recent trend of the structural design towards increased slenderness and reduced mass, stiffness and damping. Several kind of structures are prone to human-induced forces [1], e.g. footbridges [2–4], stadium grandstands [5], stairs [6,7], floors [8,9]. The wide research activity, reviewed in the papers cited above, has supported best practice guidelines [10,11], recommendations [12] and design codes (e.g. [13–17]).

Despite the intrinsic randomness of the crowd behavior, most of the human-induced force models developed so far in structural engineering are deterministic. This inadequate state of the art has been recently outlined by Racic and co-authors in their review paper [1]: *“Although the concept of variability and uncertainty is well developed in structural dynamics disciplines such as wind, wave and earthquake engineering, the stochastic concept is surprisingly underdeveloped in the area of human-structure dynamic interaction where there is a considerable randomness of the key design parameters related to the human-induced dynamic loads and structural dynamic properties.”* Variability and uncertainty are often handled in structural engineering design practice by referring to a worst-case scenario. Noticeably, this approach is not entirely suitable for the design of structures under crowd loading as footbridges. The reason is twofold: first, the crowd-structure interaction is a fully nonlinear phenomenon, where the structural response is not necessarily linear and monotonically increasing with pedestrian density. In other words, it is not always possible to predict an a priori worst-case pedestrian density. Second, a worst-case scenario for pedestrian load would induce an over conservative design of the structure and sizing of its elements, unable to meet the contemporary expectations of lightness and slenderness.

Considering this inadequacy, this study aims at contributing with a comprehensive approach for the probabilistic evaluation of the pedestrian traffic along footbridges, in the form of a multi-scale framework. The typical description of the wind flow from wind engineering is taken as inspiration and adapted to the

---

* Corresponding author.
E-mail address: luca.bruno@polito.it (L. Bruno).

http://dx.doi.org/10.1016/j.engstruct.2017.05.066
0141-0296/

Nomenclature

Symbols

$c.o.v.$	coefficient of variation
CCT	characteristic crossing time
CDF	cumulative distribution function
CL	characteristic length
CSB	Clifton Suspension Bridge
DLF_{ip}	ith Dynamic Load Factor
PDF	probability distribution function
PF	Podgorica Footbridge
RV	random variable
$COV(\cdot)$	covariance operator
$S_\cdot$, $(S^*_\cdot)$	power spectral density (dimensionless)
$X \sim y$	X distributes as y
$[\cdot]_+$	"positive part" operator
$\#\cdot$	cardinality operator (for sets)
$*$	convolution operator
$\Phi(\cdot)$	CDF of $\cdot$
$\Phi_n(\cdot)$	empiric CDF of $\cdot$
$\delta(\cdot)$	weight function for interaction distance
$\langle\cdot\rangle$	average operator
$\mathcal{N}$	Gaussian distribution
$\text{Freq}(\cdot)$	frequency of event $\cdot$
$\text{Prob}(\cdot)$	probability of event $\cdot$
$\phi(\cdot)$	PDF of $\cdot$
$\sigma(\cdot)$	standard deviation operator
$\vec{K}(\cdot,\cdot)$	interaction kernel
$d_w(\cdot)$	distance function from a wall w
ρ	pedestrian density variable
$\vec{v}$	velocity coordinate
$\vec{z}$	position of generic pedestrian
$\vec{z}_j$	position of j-th pedestrian
f	frequency variable
j, k, q	generic indices
t, (t^*)	time variable (dimensionless)
x	space variable
α, β	characteristic parameters of $\vec{v}_d^w$
Δt	time between two consecutive arrivals
δ_f	scale distance of pair-wise interaction
γ, (γ^*)	interactions decay length (dimensionless)
$\hat{\rho}$, $(\hat{\rho}^*)$	maximum density (dimensionless)
Λ	correlation length
ρ_g	global pedestrian density
ρ_l	local pedestrian density
$\rho_q, \hat{\rho}_q$	qth quantile of $\rho, \hat{\rho}_q$
$\rho_{in,g}$	incoming global pedestrian density
ρ_{in}	incoming pedestrian density
$\rho_{max,A}$	maximum density asiatic ethnicity
$\rho_{max,C}$	maximum density Caucasian ethnicity
ρ_{max}	Maximum measured density
ρ_{T_R}	T_R-return value of pedestrian density
$\tilde{\sigma}$	assigned value of standard deviation
$\vec{n}_w$	normal unit vector directed outward a wall w
$\vec{v}_d^f$	free desired velocity (to target destination)
$\vec{v}_d$	desired velocity
$\vec{v}_d^w$	desired velocity for walls avoidance
$\vec{v}_s$	social velocity
A_j	area of region C_j
A_{rec}	recording area
A_{ref}	reference area
B	width (chord) of a facility
C_j	subregion labeled by j
d^0	human body characteristic length
d_w^0	interaction range of a wall w
f_p	walking frequency
$f_{s,1v}$	natural vertical frequency
H	fully correlated fraction
L	length (span) of a facility
L_c	length of the span portion of interest
L_g	CL of the global density
L_j	length of region C_j
l_p	CL of a step
L_l	CL of the crowd inhomogeneities
L_p	CL of a pedestrian (planar)
L_{ref}	reference length
N_o	number of observations
N_p	number of pedestrians
N_R	number of regions
n_{blk}	number of time blocks
Q	pedestrian arrival rate
q	static equivalent live loads
T_c	actual (density dependent) CCT
T_g	generic time scale of the global density
T_l	smaller time scale of the local density
T_p	CCT for free pedestrians
T_R	return period
T_{avg}	amplitude of time averaging window
T_{blk}	size of a time block
T_{obs}	observation time window
T_p	CCT of a walkway
T_{sam}	sampling period
v_l	local velocity
v_p	walking speed
W_p	body Weight
x_j	centroid of C_j
y_0	position along the entrance chord

pedestrian flow phenomenology. To this aim, the uncertainties affecting the pedestrian traffic *approaching* or *crossing* a footbridge are evaluated, retaining inter-subject variabilities. The pedestrian density (i.e. the density dynamics) is adopted as principal descriptor of the crowding.

The paper develops through the following sections: in Section 2 a review of the state of art on the sources of uncertainty in human-induced loads on structures is provided. In Section 3 a multi-scale modeling framework for the probabilistic evaluation of the pedestrian traffic is defined in general and conceptual terms, on the basis of selected phenomenological features. To put the framework in practice, in Section 4 each component of the framework is modeled individually. Here, established approaches from the statistical modeling and pedestrian dynamics modeling communities are employed. Hence, procedures for their mutual integration in the framework and for the study of the uncertainty are suggested. Finally, in Section 5 the technical feasibility of the approach is discussed through two examples. Concluding remarks and research perspectives are outlined in Section 6.

2. State of the art

In this section, we review the sources of uncertainty related to human-induced loads on structures and their modeling. This analysis of the state of the art follows in spirit the well established cat-