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Computationally efficient stochastic approach for the fragility analysis of vertical structures subjected to thunderstorm downburst winds

Viet Le, Luca Caracoglia*

Department of Civil and Environmental Engineering, Northeastern University, Boston, MA 02115, USA

A R T I C L E I N F O

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A B S T R A C T

Thunderstorm downburst winds introduce considerable uncertainty in dynamical structural analysis because of wind load non-stationarity, which cannot be adequately modelled by conventional stationary wind simulations. Performance-based structural analysis in wind engineering practice, which considers uncertainty related to both error propagation and modeling simplifications, requires sampling the structural information from a large number of dynamic simulations. This task may be computationally intensive using traditional numerical integration techniques. This study examines the feasibility and advantages of utilizing a wavelet-Galerkin (WG) approach to numerically integrate the coupled stochastic dynamic equations of motion for tall building structures affected by thunderstorm wind loads. The study examines the stochastic maximum structural response at key locations. Fragility analysis is subsequently conducted using curves modelled with log-normal complementary cumulative distribution functions and surfaces modelled using logistic regression. Both a "point-like" (plate) structure and a benchmark tall building are used for verification of the proposed simulation approach.

1. Introduction and motivation

1.1. Relevance of transient thunderstorm downburst loads in wind engineering

Through exposure from the 1978 Northern Illinois Meteorological Research on Downbursts (NIMROD) and the 1982 Joint Airport Weather Studies (JAWS), thunderstorm downbursts have been recognized by the wind engineering community as phenomena deserving thorough investigation [1–4]. They can be briefly described by a central, initial touchdown point, a high-velocity non-stationary wind field and a "boundary layer" that greatly differs from that of stationary winds. The life span of a downburst follows an evolutionary path starting from an intense vertical downdraft of wind that radially diverges while decaying over a short period of time (roughly 10 to 20 min). This outburst of wind is accompanied by a translational velocity, with which the downburst travels, thus producing a transient and non-synoptic wind field.

Researchers have devoted much ongoing effort to forming models and analytical means that attempt to capture and describe the unique characteristics of thunderstorm downbursts. Oseguera & Bowles [5] originally developed a simple, three-dimensional, axisymmetric downburst model utilizing empirical shape functions. Their radial shape functions were later modified by Vicroy [6] to simulate a sharper decrease in horizontal wind speed with the relative distance from the downburst center. More recently, Abd-Elaal et al. [7] proposed supplementary, simplifying alterations to more accurately capture the vertical and the radial profiles of the horizontal wind. Other features of downbursts, such as the rapidly-evolving non-stationary turbulence, have also been examined. Experimental studies of wind loads using a microburst simulator by Zhang et al. [8] revealed that turbulence intensities increase rapidly as a function of the relative radial distance from the center (typically around 4 km for smaller downbursts categorized as "microburts"). Another experiment by Jubayer et al. [9] found modest increments of turbulence intensity with increasing height close to the ground. Beyond elevations four times larger than the height of a series of low-rise building models (tested experimentally), this trend then rose exponentially. Similar studies, emphasizing issues such as a non-homogeneous turbulence field, can be found throughout the literature (e.g. [10–12]).

Despite these research endeavors, downburst loads and their effects on structures are not yet completely understood. There is also a lack of consensus in selecting a single, physically realistic approach for thunderstorm downburst analysis. For example, extraction of the rapidly-evolving wind speed and pressure load fluctuations may be performed using methods such as discrete wavelet transform [11,13], decoupled

* Corresponding author at: Department of Civil and Environmental Engineering, Northeastern University, 400 Snell Engineering Center, 360 Huntington Avenue, Boston, MA 02115, USA.

E-mail address: lucac@coe.neu.edu (L. Caracoglia).

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Nomenclature

Symbols

$\mathbf{A}$	generic connection coefficient matrix for approximating the solution of differential equations
$\overline{\mathbf{A}}$	matrix function of a continuous operator equation
$\overline{\mathbf{A}}_{\mathbf{G}}$	generic matrix function of the algebraic system, found by Galerkin projection, used to find approximating solution coefficients
A_p	projected area of wind load, "point-like" (plate) structure
B	CAARC building width (floor-plan horizontal dimension)
b_0, b_1, b_2	logistic regression parameters
C_D	drag coefficient
C_D'	first derivative of the drag coefficient with respect to the mean horizontal angle of attack
C_{D0}	reference drag coefficient at touchdown point
C_L	lift coefficient
C_L'	first derivative of the lift coefficient with respect to the mean horizontal angle of attack
c	dimensional viscous damping term of the dynamic model describing the "point-like" (plate) structure
$c_{j_0,k}$	wavelet approximation coefficients at the j_0-th resolution order
D	CAARC building depth (floor-plan horizontal dimension)
E_{srsd}^C	cumulative square root of squared differences, estimating solution error
F_T	complementary cumulative distribution function (fragility function)
F_{Ts}	complementary cumulative distribution function (fragility function), two-parameter intensity measure
$\mathbf{f}$	right-hand-side (RHS) forcing vector of continuous operator equation
$\overline{\mathbf{f}}$	coefficients for RHS forcing vector in the domain of basis/weight functions
$\mathbf{f}_{\{\mathbf{k}\}}$	WG coefficient vector of the forcing vector $\mathbf{f}$
$\overline{f}_{x\{y\}}$, $f_{b,x\{y\}}$, $f_{s,x\{y\}}$	distributed wind loads on a continuous vertical structure (mean, buffeting, and structural excitation forces)
$g(r)$	space-intensification function
H_C	CAARC building height
H_P	elevation of lateral degree of freedom describing the wind load and response of the "point-like" (plate) structure
$I(z)$	modulation function describing the turbulence field along height z
j_0	scaling or dilation parameter (wavelet resolution)
$k_{x\{y\}}$	generalized stiffness coefficient of the model describing the response of the "point-like" (plate) structure
$M_{x\{y\}}$	generalized mass of the CAARC building (modal expansion using fundamental lateral modes)
m	lumped mass of the model describing the response of the "point-like" (plate) structure
$m_z(z)$	uniform mass per unit height of the CAARC building
N	order or "genus" of the Daubechies wavelet
N_n, N_x	original and extended computation domain, wavelet expansion
$n_{0,x\{y\}}$	fundamental-mode natural frequencies of the CAARC building
$\overline{Q}_{x\{y\}}$, $Q_{b,x\{y\}}$, $Q_{s,x\{y\}}$	mean, buffeting, and structural excitation forces: generalized loads found by modal expansion
q	structural response
$\dot{q}$	structural velocity
$\ddot{q}$	structural acceleration
R	radial length scale
R_0	horizontal-plane resultant distance between structure's reference position (projection of mass center) and initial downburst touchdown point
$R_{s,x\{y\}}$, $S_{s,x\{y\}}$	velocity modification terms of CAARC building system due to self-excited forces
r	horizontal-plane radial distance between building model and downburst
r_{max}	horizontal-plane radial distance corresponding to maximum intensification
T	duration of downburst
T_C, T_{P_i}	structural response limit state threshold for the CAARC building and "point-like" (plate) structure
t	time variable
t_0	time of downburst's maximum intensification
U	total downburst wind speed (generalized single-degree-of-freedom case, *SDOF*)
U_{2D}	total downburst wind speed (generalized two-degree-of-freedom case, *2DOF*)
$\overline{U}$	resultant "mean" wind speed of the downburst
$\overline{U}_{\text{Vicroy}}$	maximum "mean" wind speed of Vicroy profile
$\overline{U}_r$	radial "mean" wind speed of downburst
U_{tran}	horizontal translation speed of downburst
$\overline{U}_z$	downburst "mean" wind speed at height z
$u(x)$	solution of the continuous operator equation
u'	wind turbulence in the direction of the tilted, "x'"-axis
u^*	Galerkin approximating solution
$\overline{\mathbf{u}}$	approximating coefficients of the Galerkin solution
u_k	vector of unknown coefficients associated with the basis functions of the Galerkin expansion
$\mathbf{u}_{\{\mathbf{k}\}}$	WG coefficient vector of solution $u(x)$
v'	horizontal wind turbulence component in the direction of the tilted, "y'"-axis
X_0	horizontal-plane "x"-coordinate of initial touchdown of downburst
x	generic variable
Y_0	horizontal-plane "y"-coordinate of initial touchdown of downburst
z	vertical coordinate of building models
z_{max}	elevation of the maximum "mean" wind speed from the ground
β	horizontal-plane angle between $\overline{U}_r$ and U_{tran}
γ	instantaneous angular fluctuation due to wind turbulence
ε	generalized structural response variables
$\zeta_{x\{y\}}$	generalized fundamental-mode damping ratio of the dynamic models describing either the "point-like" (plate) structure or benchmark tall building
θ	horizontal-plane "mean" directional angle along which $\overline{U}$ acts
μ	location parameter of log-normal CCDF
$\Pi(t)$	time-intensification function
ρ	air density
σ	scale parameter of log-normal CCDF
Φ	log-normal cumulative distribution function model
$\phi_{x\{y\}}(z)$	mode shape functions of the benchmark CAARC building (fundamental modes)
φ	scaling function of the Daubechies wavelet
φ_k	basis function of Galerkin approach
ψ_l	weight function of the Galerkin approach
$\Omega^{0,0}$	2-term connection coefficient matrix, containing $\Omega^{0,0}_{j,k-l}$
$\Omega^{0,1}$	2-term connection coefficient matrix, containing $\Omega^{0,1}_{j,k-l}$
$\Omega^{0,2}$	2-term connection coefficient matrix, containing $\Omega^{0,2}_{j,k-l}$
$\Omega^{0,0}_{k-l}$, $\Omega^{0,1}_{k-l}$, $\Omega^{0,2}_{k-l}$	2-term connection coefficient at the derivative orders 0, 0 and 1, 0 and 2
$\omega_{0,x\{y\}}$	fundamental-mode angular frequencies of the benchmark CAARC building in rad/s