MODERN STRUCTURAL DESIGN FOR WIND AS AN INTERDISCIPLINARY PROCESS

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This paper is dedicated to Dr. Horea Sandi of the Romanian Academy of Technical Sciences, a luminary of Romanian and international structural engineering research.

ABSTRACT

This paper presents a brief overview of the historical evolution of approaches to the design of structures for wind loads. The interdisciplinary nature of this field is noted, involving as it does elements of micrometeorology, extreme wind climatology, aerodynamics, wind tunnel testing, structural dynamics, aeroelasticity, structural reliability and, last but not least, structural engineering. Technological advances in the areas of simultaneous pressure measurements and "big data" processing are shown to have led to a new paradigm in the relation between the structural designer and the wind engineer, wherein the former is in full control of all aspects of the modern design process, referred to as database-assisted design.

KEYWORDS: Aerodynamics, extreme wind climatology, micrometeorology, structural dynamics, structural engineering, structural reliability, wind engineering.

Modern structural design for wind emerged in the 1960s as a synthesis of the following developments:

- Modeling of the neutrally stratified atmospheric boundary layer flow, including (i) the variation of wind speeds with height above the ground as a function of upwind surface roughness, and (ii) the atmospheric turbulence.
- Modeling of pressures induced on a rectangular building face by atmospheric flow normal to that face.
- Probabilistic modeling of extreme wind speeds.
- Frequency domain modeling of the dynamic along-wind response produced by atmospheric flow normal to a building face.

The increase of wind speeds with height above ground had been reported by Helmann[2] in 1913 and by Pagon[3] in 1935, and its aerodynamic effects had been researched under Prandtl's supervision by Flachsbart[4], until the latter's dismissal by the Nazi authorities following his refusal to divorce his Jewish wife. A pioneering procedure for the estimation of the dynamic response of flexible bodies in turbulent flow had been developed by Liepmann[5] in 1951; and the probabilistic modeling of extreme values had been considered for geophysical applications by Gumbel, among others[6]. However, a synthesis of those developments, and contributions to their advancement, were

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[2] G. Hellman, "Ueber die Bewegung der Luft in den tiefsten Schichten der Atmosphaere," Meteorologische Z., 34 (1916), p.273.

[3] W. W. Pagon, "What Aerodynamics can teach the civil engineer," Engineering News-Record. 348-353, (March 15, 1934), 41-43 (July 12, 1934), 456-458 (October 11, 1934), 814-819 (December 27, 1934), 582-586 (April 25, 1935), 665-668 (May 9, 1935), 742-745 (May 23, 1935), 601-607 (October 31, 1935).

[4] O. Flachsbart, "Winddruck aud offene und geschlossene Gebauede," Ergebnisse der Aerodynamischen Versuchanstalt zu Goettingen, IV Lieferung, L. Prandtl and A. Betz (eds.) Oldenburg, Munich and Berlin (1932).

[5] H.W. Liepmann, "On the application of statistical concepts to the buffeting problem," J. Atmosph. Sci. 19 (Dec. 1952), 793-800, 822.

[6] E. Gumbel, Statistics of Extremes," Columbia Univ. Press, New York (1958).

first achieved in the 1960s by Davenport[7,8], partly under the supervision of his doctoral thesis advisor, Sir Alfred Pugsley, of the University of Bristol. However, Davenport's synthesis was not sufficiently broad to account for wind effects induced by vorticity shed in the wake of the structure or by winds not normal to a building face. Specialized wind tunnels were therefore developed in 1960s with a view to simulating the atmospheric boundary layer flow and its aerodynamic and dynamic effects on structures.

An improvement of the capability to determine wind effects objectively was achieved in the early 1980s with the development of the high frequency force balance (HFFB). The HFFM method as originally applied provided data on the shears and moments at the base of the building but no information on the distribution of the wind loading with height. That information is needed because to any given base shear and moment there can correspond more than one wind load distribution with height. In its absence, the design of the structural members must be based largely on guesswork, especially for buildings influenced aerodynamically by neighboring structures.

The development of the pressure scanner in the 1990s allowed the simultaneous measurement of pressure time histories at large numbers of taps on the building facades. This resulted in an improvement over HFFB estimates of the response by providing, in addition to data on base moments and shears, information on the distribution of wind pressures with height. That information can result in static wind forces at the building's floor levels that are consistent with the measured base moments. However, it can be easily shown that those static wind forces, used by the structural engineer to determine internal forces in the structural members, produce estimates of those forces that can differ substantially from the estimates based on the randomly fluctuating wind loads. Also, even with the benefit of pressure measurements, accounting for directionality in the estimation of wind effects with specified mean recurrence intervals is still done in current practice either largely "by eye," or by a procedure found by structural engineers to be prohibitively opaque[9], in addition to being based on guessed-at structural properties and unrealistic wind climatological assumptions[10]. These limitations notwithstanding, in the absence of a physically more realistic approach, HFFB can be used to good effect for the fast aerodynamic assessment of potential building configurations and orientations in the preliminary phase of the design process.

However, for final structural design purposes a more powerful and effective approach has recently been developed: database-assisted design (DAD). The interdisciplinary character of the design of structures for wind is most clearly demonstrated by considering the database-assisted design process. DAD implements a time-domain technique that allows the efficient exploitation of the wind climatological and aerodynamic information. Its aim is to determine wind effects rigorously, transparently, and without unnecessary and onerous simplifications. Since it is required that member demand-to-capacity indexes (i.e., the left-hand sides of the interaction equations) be close to unity, DAD computes DCIs iteratively until this design criterion is satisfied. Inefficiencies inherent in the current practices are eliminated, and a logical and effective interface between wind engineering and structural design is achieved, which results in structural designs with more "muscle" and less "fat".

The DAD approach has redefined the wind and structural engineer's complementary contributions to the structural design process. As noted earlier, the wind engineer' first task is to

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[7] Ibidem.

[8] A.G. Davenport, "Gust Loading Factors," J. Struct. Div, ASCE, 93 (1967), 11-34

[9] SOM -- Skidmore Owings and Merrill LLP (2004). Report on Estimation of Wind Effects on the World Trade Center Towers, Appendix D. http://wtc.nist.gov/NCSTAR1/NCSTAR1-2intex.htm;
also in E. Simiu (2011). Design of Buildings for Wind, Wiley, Hoboken, Appendix 5.

[10] X. Zhang and X. Chen, X.. "A refined process upcrossing rate approach for estimating probabilistic wind load effects with consideration of directionality." J. Struct. Eng., (2016), doi:10.1061/(ASCE)ST.1943-541X.0001625, 04016148.

participate, alongside the architect, the structural engineer and other design professionals, in the process that determines the building's preliminary configuration and orientation. The wind engineer's next and only other task is to provide, in formats suitable for use by the structural engineer, the wind climatological and aerodynamic pressure coefficient data required as input to the final design process.

Once these data are available, the structural engineers are in full control of the structural design. Their first task is to produce a preliminary structural design, that is, a structural system with specified configuration and preliminary member sizes based on a simplified model of the wind loading (e.g., a static wind loading based on standard provisions). Following the preliminary sizing of the structural members, the structural engineer determines the structure's stiffness matrix and influence coefficients as affected by secondary effects due to products of gravity loads by the building's horizontal displacements. Next, the directional wind climatological and aerodynamic pressure time history data are transformed into time histories of aerodynamic loads applied to each floor or group of floors. To these loads are added inertial forces determined by analyzing the structure's dynamic behavior. The sums of the applied aerodynamic loads and the dynamic loads are referred to as the effective wind loads. A transparent and effective approach to determining wind effects with specified mean recurrence intervals proceeds by constructing response surfaces for the wind effects of interest (DCIs, inter-story drift, accelerations). The response surfaces are properties of the structure representing load effects as functions of wind speeds and directions, and are developed by using (i) effective wind loads corresponding to those speeds and directions, (ii) influence coefficients that transform the loads into the requisite load effects, and (iii) gravity loads prescribed by standards. The response surfaces are then used, in conjunction with matrices of directional wind speeds and simple parameter-free distributions to determine the requisite wind effects with specified mean recurrence intervals. If the uncertainties in the wind loading differ significantly from the typical uncertainties assumed in the development of the standard, the specified wind load factors or the corresponding mean recurrence intervals of the design wind effects are modified with respect to those specified in standards. The peak floor displacements and accelerations are in some cases reduced through the use of mitigation devices such as tuned mass dampers.

The wind effects determined by the DAD process must satisfy applicable design criteria. If the design criteria are not satisfied the members are re-sized via iterations of that process. These are performed until the design criteria are satisfied to the extent allowed by constructability and serviceability constraints.

To summarize, the DAD approach involves elements from the following disciplines:

AS AN INTERDISCIPLINARY PROCESS

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