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MODERN PRESSURE MEASUREMENT TECHNOLOGY AND STRUCTURAL DESIGN FOR WIND: A NEW COLLABORATIVE PARADIGM FOR WIND AND STRUCTURAL ENGINEERS

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Summary. Against a brief historical overview, this paper presents the Database-assisted Design (DAD) approach, a conceptually simple, transparent, and rigorous approach to structural design for wind, which fully exploits the potential of modern computational capabilities and pressure measurement technology. A novel collaborative framework between wind and structural engineers assures the effectiveness of this approach and establishes clear lines of responsibility for their respective contributions to the design process. Wind effects with design mean recurrence intervals are determined by DAD more accurately than is possible by using conventional methods for estimating aerodynamic loads, dynamic effects, and wind directionality effects. The DAD approach is consistent with Building Information Modeling (BIM) requirements, and is in principle applicable to most structures for which wind pressures are determined by aerodynamic testing or CFD methods.

1 INTRODUCTION

The recent development of simultaneous pressure measurement technology, and the availability of powerful computational capabilities, have offered the potential for achieving significantly improved structural designs. To fully realize this potential, a novel, computer-intensive ("big data") time-domain approach has been developed, known as database-assisted design (DAD).

In DAD the wind engineering laboratory's task consists of providing the structural engineer with the requisite wind climatological and aerodynamic pressure coefficient data. The structural engineer's task is to use those data as input to specialized software, the output of which consists of member demand-to-capacity indexes (DCIs) and appropriate measures of the structure's motions. The software performs the following operations: (i) using the aerodynamic pressure data to determine the time histories of the stochastic aerodynamic loads acting on the structure; (ii) determining stiffness matrices by accounting for secondary effects due to moments induced by gravity loads on the deformed structure (iii) performing the dynamic analyses that yield the time histories of the inertial loads; (iv) rigorously combining, via simple summations, time histories of simultaneous wind effects induced by the wind-induced forces; (v) rigorously accounting for wind directionality, and (vi) determining DCIs, displacements and accelerations with the respective requisite MRIs. It follows from this division of tasks that once the requisite wind climatological and aerodynamic data are available, the structural designer is in full control of the design process. This approach parallels the aseismic design process wherein, once the basic information required to define the seismic loads is available, the design process is controlled by the structural engineer. The conceptual simplicity and transparency of the DAD approach allow the clear and effective scrutiny of the design by owners, building officials, and insurers, and make it posible to achieve the requisite accountability of the entities responsible for contributions to the design for wind. A rare public analysis of the wind engineering contributions has clearly shown that opacity effectively thwarts accountability.[1]

Section 2 is devoted to a brief historical overview. Section 3 presents a review of the DAD approach and notes that, as CFD methods evolve, they may be expected to be a valid substitute for wind tunnel simulations. Section 4 briefly discusses the extent to which elements of the DAD approach may be applicable to tension structures. Section 5 pesents the conclusions of this work.

2 BRIEF HISTORICAL OVERVIEW

Procedures used during the past half-century to design structures for wind are rooted in advances achieved in the modeling of turbulent atmospheric boundary layer flow, the probabilistic modeling of the extreme wind speeds, and the dynamic along-wind response produced by atmospheric flow normal to a building face. The increase of wind speeds with height above ground was first reported by Helmann in 1916.[2] Extreme value probabilistic models for geophysical applications were developed by Gumbel in the 1940s.[3] Aerodynamic effects of turbulent flows were first researched by Flachsbart in 1932[4] (Fig. 1).[1] A pioneering approach to the estimation of the dynamic response of bodies immersed in turbulent flow was developed by Liepmann in 1951[7]. However, a synthesis of these developments was first achieved in the 1960s by Davenport[8, 9], a University of Bristol student of the eminent British engineer Sir Alfred Pugsley. That synthesis was not capable of accounting for wind effects induced by vorticity shed in the wake of the structure, for winds skewed with respect to a building face or affected by the presence of neighboring buildings, or for aeroelastic behavior. Specialized wind tunnels were therefore developed in 1960s with a view to simulating the atmospheric boundary layer flow and its aerodynamic, dynamic and aeroelastic effects on structures.

During the 1970s wind tunnel techniques were not sufficiently developed to allow accurate measurements of wind effects for structural design purposes. Information on wind effects was based in large part on non-simultaneous pressures measured at typically small numbers of taps, with unavoidable and, in many instances, significant errors.

[1] Flachsbart was dismissed by the Nazi authorities for refusing to divorce his Jewish wife and could not complete his wind engineering research.[5] Some of his results were re-discovered independently by Jensen in the 1960s.[6]

An improvement in the capability to determine wind effects was achieved in the early 1980s with the development of the high frequency force balance (HFFB).[10] The HFFB approach is applied to tall buildings designed to experience no aeroelastic response under extreme wind speeds attainable in practice. HFFB provides time histories of the effective (aerodynamic plus dynamic) base moments induced by the wind loads. Its chief drawback is that it provides no data on the distribution of the wind loading with height, since there is no unique

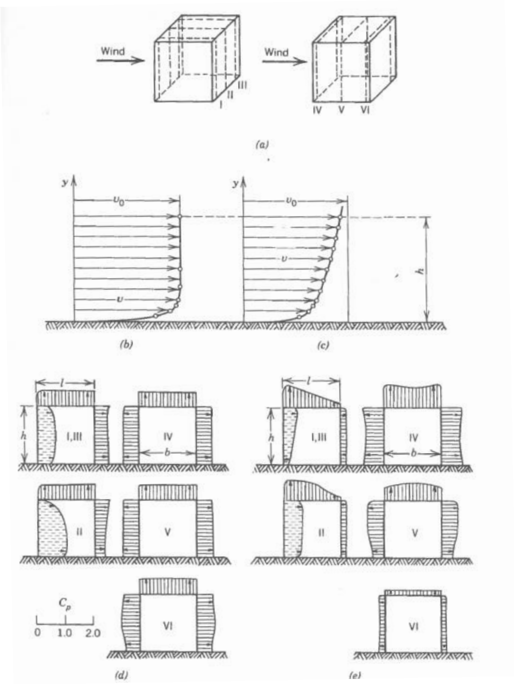

Figure 1. Results of model tests in smooth and boundary-layer flow. From *Ergebnisse der aerodyn. Versuchanstalt zu Goettingen,* IV Lieferung, L. Prandtl and A. Betz (eds.) (1932).

correspondence between that distribution and the base moments or shears. The loading information needed to calculate the DCIs (i.e., the quantities required for the sizing of the structural members) therefore depends largely on guesswork, especially for buildings influenced aerodynamically by neighboring structures. In addition, HFFB estimates of dynamic response are based on the assumption that the fundamental sway modal shapes are linear and that higher modes of vibration are negligible. The HFFB approach is nevertheless useful in the preliminary phase of the design process, as it allows the rapid, qualitative aerodynamic assessment of building configurations, orientations and facade features such as balconies; it is, however, unsatisfactory for final design purposes.

The wind load distribution problema was solved in the 1990s through the use of large numbers of pressure taps on the building facades. Nevertheless, wind engineeering laboratories still use the HFFB for the estimation of dynamic effects. Such use is no longer necessary, since the structural engineer has the ready capability – not available to the wind engineer -- of accounting effectively for the actual fundamental modal shapes in sway and torsion, as well as for higher modes of vibration. In addition, should changes in the structural features occur during the design process, the structural engineer can easily update the estimates of the dynamic effects with no need for unwieldy interactions with the wind engineering laboratory.

3 DATABASE-ASSISTED DESIGN

The DAD technique relies on a natural and effective division of tasks between wind engineers and structural engineers.

3.1 Wind Engineering Tasks

Following the preliminary design phase, the wind engineer's role is to provide, in formats suitable for use by the structural designer and for Building Information Modeling[11] (BIM) purposes, (i) the requisite wind speed data as affected by the micrometeorological features of the building site, and (ii) the aerodynamic pressure coefficient time series measured in the wind tunnel at a sufficient number of pressure taps. The wind engineer must also provide estimates of the uncertainties in the data. As CFD methods evolve and progress occurs toward gaining acceptance of such methods by the structural engineering community, numerical simulations of wind loading will increasingly be used in lieu of measurements. CFD may be especially advantageous for estimating the aeroelastic response of certain types of tension structures in which wind effects change the structures' shape, thus affecting the aerodynamic load.[12]

3.2 Structural Engineering Tasks

The structural designer's first task is to perform a preliminary design of the structure's main wind force resisting system, using simplified wind loads specified in conventional standard provisions. The preliminary, conventional design is denoted by D_0. The structural designer's subsequent tasks are automated – see [13]. These tasks include determining the system's mechanical properties for the design D_0, i.e., (i) the effective stiffness matrix that accounts for P-Δ and P-δ effects, (ii) the requisite influence coefficients, and (iii) modal shapes and frequencies. Time histories of directional applied aerodynamic forces are then calculated from directional pressure coefficient records by apportioning to each floor or group of floors pressures weighted by the respective taps' tributary areas. This operation is performed for mean wind speeds ranging from, say, 20 m/s to 70 m/s in increments of, say, 10 m/s, with directions ranging from, say, $0 \leq \theta < 360°$ in increments of, say, 15 °. Dynamic analyses are performed for each of those wind speeds and directions to obtain the respective time histories of the inertial forces induced by the aerodynamic loads. The time histories of the effective wind-induced loads acting on the structure consist of the sums of the aerodynamic and inertial force time histories.

Checking the adequacy of the preliminary design D_0 requires determining the structural members' peak demand-to-capacity indexes (DCIs) corresponding to the specified design mean recurrence interval $\bar{N}$. This phase of the design process is performed as follows:[14]

1. DCI time histories are determined for each of the wind speeds and directions for which the dynamic analyses have been performed. For example, for DCIs of steel members subjected to flexure and axial forces, the following design criteria for strength are specified in:[15]

$$\text{tarIf } \frac{P_r}{\phi P_n} \geq 0.2,\ \frac{P_r}{\phi P_n} + \frac{8}{9}\left(\frac{M_{rx}}{\phi_b M_{nx}} + \frac{M_{ry}}{\phi_b M_{ny}}\right) \leq 1.0 \tag{1a}$$

$$\text{If } \frac{P_r}{\phi P_n} < 0.2,\ \frac{P_r}{2\phi P_n} + \left(\frac{M_{rx}}{\phi_b M_{nx}} + \frac{M_{ry}}{\phi_b M_{ny}}\right) \leq 1.0 \tag{1b}$$

Equations 1 are called *design interaction equations*; their left-hand sides are called *demand-to-capacity indexes* (DCIs). In Eqs. 1 the required strengths are based on Load and Resistance Factors Design (LRFD) load combinations that include gravity loads; P_r and P_n are the required and available tensile or compressive strength; M_{rx} and M_{nx} the required and available flexural strength about the strong axis; M_{ry} and M_{ny} the required and available flexural strength about the weak axis; ϕ, ϕ_b are resistance factors. In the ASCE 7-16 Standard[16] no wind load factor is specified. To compensate for its absence, the design mean recurrence interval is augmented commensurately, for example from 50 to 700 years.

In Eqs. 1 the time histories of the internal forces are sums of the time histories of the effective aerodynamic forces W_k acting on the structure at locations identified by the index k, times the respective applicable influence coefficients r_{mk}. The coefficient r_{mk} represents the effect being considered (e.g., a bending moment induced in the cross section m by a unit force normal to the structure's surface acting at point k; $m = 1, 2, \ldots, m_{max}$ and $k = 1, 2, \ldots, k_{max}$). All wind load combinations are automatically performed via these summations.

For each of the m_{max} cross sections of interest and for each wind speed and direction for which dynamic analyses have been performed, the peaks of the DCI time series, $\max_t(\mathrm{DCI}_m) \equiv \mathrm{DCI}_m^{pk}$, are obtained using standard procedures (see, for example,[17]). The results of the computations are represented as peak DCI response surfaces (Fig. 2).

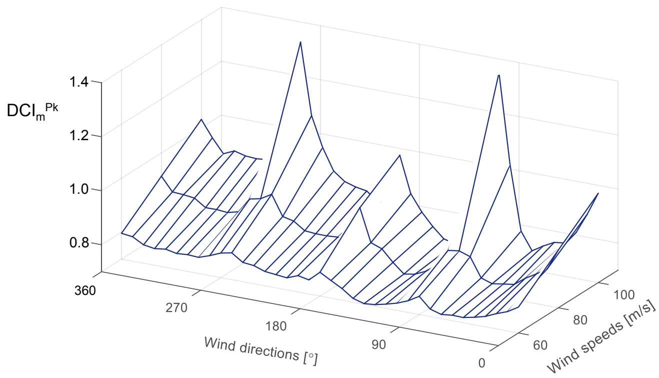

Figure 2. Response Surface for, peak DCI of member subjected to bending and axial force.

2. In the wind speed matrix $[U_{ij}]$ provided by the wind engineering laboratory, where i and j identify the storm event and wind direction, respectively, the entries U_{ij} are replaced by the

quantities $\mathrm{DCI}_m^{pk}(U_{ij})$ taken from the response surface for $\mathrm{DCI}_m{}^{pk}$.

3. The matrix $[\mathrm{DCI}_m^{pk}(U_{ij})]$ is transformed into a vector $\{\max_j(\mathrm{DCI}_m^{pk}(U_{ij}))\}^{\mathrm{T}} \equiv \{\mathrm{DCI}_m^{pk}(U_i)\}^{\mathrm{T}}$, (T denotes transpose) by disregarding in each row i all DCIs lower than $\mathrm{DCI}_m^{pk}(U_i)$, since only the largest DCI occurring in each of the storm events is of interest from a design viewpoint.

4. The quantities $\mathrm{DCI}_m^{pk}(U_i)$ are rank-ordered, and non-parametric statistics are typically used in conjunction with the mean annual rate of storm arrival λ to obtain the quantities $\mathrm{DCI}_m^{pk}(\bar{N})$.

If the peak $\mathrm{DCI}_m^{pk}(\bar{N})$ so determined is approximately equal to unity, the design for strength is acceptable. Inter-story drift and top floor accelerations are similarly checked. Typically, the preliminary design D_0 does not satisfy the strength and/or serviceability design criteria. The structural members are then re-sized to produce a modified structural design D_1. This iterative process continues until the final design is satisfactory; convergence is generally rapid. A deliberately simple illustration of the process just described follows.

Directional Wind Speed Matrix. Consider the 3 x 4 matrix of wind speeds (in m/s):

$$[U_{ij}] = \begin{bmatrix} 34 & \mathbf{45} & 32 & 44 \\ 37 & 39 & 36 & \mathbf{51} \\ 42 & 44 & 35 & \mathbf{46} \end{bmatrix} \tag{2}$$

at the site of the structure. Under the convention inherent in the notation U_{ij} this matrix corresponds to three storm events and four wind directions, that is, i = 1, 2, 3 and j = 1, 2, 3, For example, the wind speed that occurs in the second storm event from the third direction is U_{23} = 36 m/s. (The entries in the wind speed matrix could, for example, be mean hourly speeds at the top of the structure, with direction j over terrain with suburban exposure.) In the matrix of Eq. 2 the largest wind speeds in each of the three storms are indicated in bold type.

Transformation of Matrix $[U_{ij}]$ into Matrix $[\mathrm{DCI}_m^{pk}(U_{ij})]$ of peak DCIs. The matrix $[U_{ij}]$ is transformed into the matrix $[\mathrm{DCI}_m^{pk}(U_{ij})]$ by substituting the quantities $\mathrm{DCI}_m^{pk}(U_{ij})$ for the quantities U_{ij}. Assume that the result of this operation is the matrix

$$[\mathrm{DCI}_m^{pk}(U_{ij})] = \begin{bmatrix} 0.70 & \mathbf{1.02} & 0.80 & 0.68 \\ 0.83 & 0.77 & \mathbf{1.01} & 0.91 \\ \mathbf{1.07} & 0.98 & 0.96 & 0.74 \end{bmatrix} \tag{3}$$

Transformation of Matrices of Peak Wind Effects $[\mathrm{DCI}_m^{pk}(U_{ij})]$ Into Vectors $\{\mathrm{DCI}_m^{pk}(U_i)\}^{\mathrm{T}}$. The peak wind effects induced by the wind speeds occurring in storm event i depend upon the wind direction j. It is only the largest of those wind effects, that is, $\mathrm{DCI}_m^{pk}(U_i)$, (i = 1, 2, 3), that are of interest from a design viewpoint. These largest DCIs, shown in bold type in Eq. 3, form a vector $\{1.02, 1.01, 1.07\}^{\mathrm{T}}$. Note that $\mathrm{DCI}_m^{pk}(U_3)$ is not necessarily induced by the speed $\max_j(U_{3j})$. For example, $\mathrm{DCI}_m^{pk}(U_3) = \max_j(\mathrm{DCI}_m^{pk}(U_{3j})) = 1.07$ is not induced by the speed $U_3 = \max_j(U_{3j}) = U_{34}$ = 46 m/s, but rather by the speed U_{31} = 42 m/s. The components of the vector $\{\mathrm{DCI}_m^{pk}(U_i)\}^{\mathrm{T}}$ constitute the sample of the largest DCIs that occur in each of the i storm events (in this example i = 1, 2, 3) at the cross section m being considered.

Estimation of Wind Effects with Specified MRIs. The variate DCI_m^{pk} with an MRI N_f, where N_f is the number of average time intervals between successive storms, corresponds to a CDF ordinate $P = 1 - 1/N_f$. However, the designer is interested in the variate DCI_m^{pk} with an MRI $\bar{N}$ in *years*. Since the mean annual rate of storm arrival is λ, $\bar{N} = N_f / \lambda$. For example, if the storms being considered are tropical cyclones, it is typically the case that $\lambda < 1$ storm/year, so $\bar{N} > N_f$. Therefore, the variate DCI_m^{pk} with an MRI $\bar{N}$, $\mathrm{DCI}_m^{pk}(\bar{N})$, corresponds to the ordinate $P = 1 - 1/(\lambda\bar{N})$ of the CDF fitted to the data sample $\max_j(\mathrm{DCI}_{m,ij}^{pk})$ (i = 1, 2, …, n). For a detailed example of the application of non-parametric statistical approach see.[18]

If the specified design MRIs are much longer than the wind speed record length, the application of non-parametric statistics may require the development by the wind engineering laboratory of large synthetic directional wind speed data sets. The development entails three steps. First, the measured directional wind speeds are processed by the wind engineer so that they are consistent with the micrometeorological features of the structure's site. Second, the directional wind speed data so obtained are fitted to Extreme Value Type I distributions, which are widely accepted as appropriate for the probabilistic description of extreme wind speeds. A probability distribution is fitted to the wind speeds from each direction j. Third, the Extreme Value Type I distributions are used to develop by Monte Carlo simulation the requisite sets of directional extreme wind speed data.[19] These sets are then provided by the wind engineering laboratory to the structural designer.

The analysis and design process briefly described so far is represented in the flow chart of Fig. 3. The aerodynamics and wind climatological data provided by the wind engineering laboratory must be fully documented and recorded. This allows the development of Building Information Modeling (BIM), and enables full traceability and scrutiny of the project by its stakeholders – the structural engineer, the owner, the insurer, and the building official.

The DAD approach is designed to be transparent and fully understandable to project stakeholders. The wind engineering laboratory performs wind engineering tasks, for which it is fully equipped, and the structural engineering office performs structural engineering tasks, for which it has the structural engineering and computational wherewithal. This division of tasks between the wind and the structural engineer is efficient, and establishes clear lines of responsibility. The interface between the wind engineering and structural engineering phases of the design is smooth and entails no loss of information. In particular, as noted earlier, wind effects, including DCIs induced simultaneously by loads acting on all building facades, are determined objectively via simple weighted summations of contributions to those effects, with no need for subjective combination factors. Higher modes of vibration and any modal shape are readily accounted for. Wind effects with specified MRIs obtained by accounting for wind directionality are determined transparently, are consistent with the structural properties inherent in the final structural design, and are determined more accurately than is possible by using conventional methods for determining aerodynamic loads, dynamic effects, wind directionality effects, and mean recurrence intervals of wind effects.

The DAD approach was successfully applied to the structure depicted in Fig. 4. This case study showed that only one or two iterations are needed to satisfy the requisite design criteria, and that the computing times required for the design of as many as thousands of different members are fully compatible with typical structural engineering office capabilities.

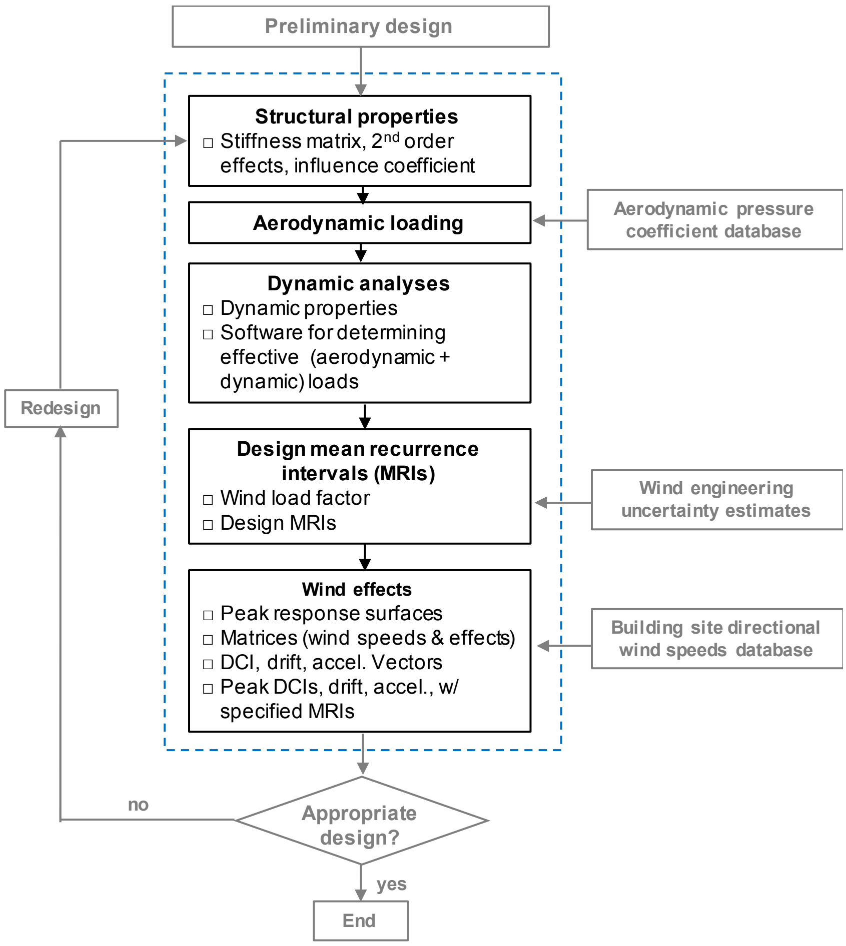

Figure 3. Flow chart representing DAD approach to structural design for wind.

4 MEMBRANE STRUCTURES

A vast literature is available on capabilities for the estimation of stresses and deformations in membrane structures as functions of their loading (see, for example[20]), -- in particular of their wind loading. The use of those capabilities requires an accurate definition of the wind loads and their variation in space and time.

For enclosed membrane structures for which aeroelastic oscillations of the membrane are not acceptable (e.g., structures similar in this respect to the Denver airport), wind pressures can be obtained by measurement. Whenever posible, the measurements should be conducted in large-scale aerodynamic facilities allowing the use of relatively large models. Examples are the large-scale boundary-layer aerodynamic facilities at the Florida International University[21] and the Insurance Institute of Business and Home Safety,[22] which allow portions of the structure and/or the entire structure to be tested at Reynolds numbers larger than 10^6, with detailed modeling of relatively small features of the structure that may influence its

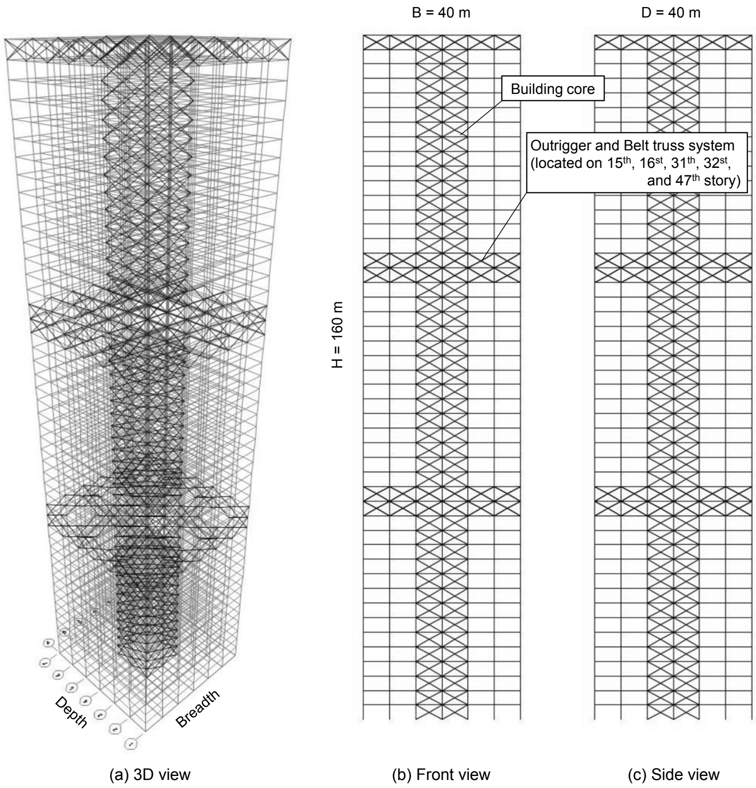

Figure 4. Schematic views of structural system for the building prototype.

aerodynamics. Simple experimental techniques are available that can be used to identify zones of high pressures (”hot spots”).[23] Pressure time histories can then be measured simultaneously at and around those zones using the pressure scanner, thus allowing the estimation of wind loads over small areas and over the tributary areas of the various members and member assemblies of the supporting structure. For open membrane structures for which no aeroelastic effects are permitted, the wind tunnel model would have to make allowance for the presence between the upper and lower roof surface of the plastic tubes that connect the taps to the pressure scanner, meaning that the scale of the prototype roof thickness would differ from the overall model scale. The extent to which this causes unacceptable aerodynamic distortions would need to be checked. The pressure coefficient time histories and the wind climatological data can be used to obtain the requisite information on the structure’s state given the specified MRIs, which can be estimated by accounting for wind directionality as shown in Section 2.

An alternative to the measurement of pressures in aerodynamic facilities is the use of CFD methods. Such methods can be applied to study the behavior of structures that may be assumed to be rigid, as well as of structures experiencing aeroelastic effects – see, e.g.,[12, 24].

One well-known drawback of CFD methods applied to civil engineering structures is the lack of confidence in results obtained in the absence of ad-hoc validation. However, in view of the weight of other types of uncertainty, including the dominant weight of uncertainties in the wind speeds, coefficients of variation of pressure coefficient uncertainties as large as 15 % result in an increase of the design wind load by less than approximately 10 %.[25]

5 CONCLUSIONS

The brief historical review of structural design for wind presented in this paper notes the progressively improved modeling of the effects of wind on structures and the decreasing role of subjective estimates as measurement techniques have evolved. It was noted that the High Frequency Force Balance approach provides no information on the distribution of the wind loads with height, rendering impossible an accurate estimation of the structural members' demand-to-capacity indexes. The need to eliminate or reduce shortcomings of current conventional practices has given rise to the development of a time-domain, computer-intensive, iterative database-assisted design (DAD) approach that fully exploits the potential of simultaneous measurements of aerodynamic pressures acting on the structure. For any specified mean recurrence interval DAD determines peak demand-to-capacity indexes used for member sizing, peak inter-story drift values, and peak top-floor accelerations. The DAD approach accounts rigorously for wind directionality effects and for elaborate combinations of multiple time histories of wind effects.

DAD entails a natural and effective dicvision of tasks between the wind engineering laboratory and the structural design office, thus establishing clear lines of responsibility. The role of the wind engineer in the final design process is to produce the requisite micrometeorological, wind climatological, and aerodynamic information in formats suitable for effective use by the structural engineer and for incorporation into building information modeling (BIM). In the interest of accuracy, dynamic analyses are performed by the structural engineer. This practice has the added advantage of avoiding impractical back-and-forth between wind and structural engineers as the strcutral design undergoes successive changes during the course of the design process. The wind engineering laboratory thus performs wind engineering tasks, for which it is fully equipped, and the structural designer performs structural engineering tasks, for which it has the structural engineering and computational wherewithal. The interface between the wind engineering and structural engineering phases of the design is natural, smooth, and entails no loss of information. Finally, DAD makes it possible to achieve, to the extent permitted by constructability and serviceability constraints, the differentiated and risk-consistent design of the structural members. Whether applied by using measured or numerically simulated aerodynamic pressure data, DAD results in transparent designs and safer, more economical structures than can be achieved by earlier practices.

REFERENCES

[1] Skidmore Owings and Merrill LLP, *Report on Estimation of Wind Effects on the World Trade Center Towers,* NCSTAR1-2, Appendix D dated 13 April 2004 (http://wtc.nist.gov/NCSTAR1/NCSTAR1-2index.htm).

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

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

[4] O. Flachsbart, "Winddruck auf offene und geschlossene Gebäude," *Ergebnisse der aerodynamischen Versuchanstalt zu Göttingen,* IV Lieferung, L. Prandtl and A. Betz (eds.) Oldenburg, Munich and Berlin (1932).

[5] E. Plate, Personal communication (1995).

[6] M. Jensen and N. Franck (1965). *Model-scale Tests in Turbulent Wind*, Danish Technical Press.

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

[8] A.G.Davenport, "The application of statistical concepts to the wind loading of structures," *Proc. Inst. Civ. Eng.,* **19** (1961), 449-472.

[9] A.G. Davenport, "Gust Loading Factors," *J. Struct. Div,* ASCE, **93** (1967), 11-349.

[10] T. Tchantz (1982). "Measurement of Total Dynamic Loads Using Elastic Models with High Natural Frequencies," *Wind Tunnel Modeling for Civil Engineering Applications,* T.A. Reinhold, ed. Cambridge University Press, pp. 296-312.

[11] *Building Information Modelling.* http://www.arup.com/services/building_modeling, last access April 12, 2017.

[12] M. Heil, L. H. Andrew, and B. Jonathan (2008), "Solvers for large-displacement fluid-structure interaction problems: segregated versus monolithic approaches," *Comp. Mech.* **43** (1) 91-101.

[13] S. Park and D. Yeo*, Database-Assisted Design of Steel and Reinforced Concrete Structures for Wind: Concepts, Software, and User's Manual*, NIST Technical Note, National Inst. of Standards and Technology, in review (July 2017).

[14] E. Simiu and D. Yeo (2015). "Advances in the design of high-rise structures by the wind tunnel procedure: Conceptual framework." *Wind and Structures* **21** (5) 489-503.

[15] ANSI/AISC. *Specification for Structural Steel Buildings*. Chicago, Illinois: American Institute of Steel Construction (2010).

[16] ASCE/SEI 7-16. *Minimum Design Loads for Buildings and Other Structures.* Reston, VA: American Society of Civil Engineers, 2016.

[17] A. L. Pintar, D. Duthinh, and E. Simiu, "Estimating peaks of stationary random processes: a peaks-over-threshold approach," *J. Risk and Uncertainty in Eng. Systems* (in press).

[18] E. Simiu, *Design of Structures for Wind*, Hoboken: Wiley (2011), p. 158.

[19] D. Yeo, "Generation of Large Directional Wind Speed Data Sets for Estimation of Wind Effects with Long Return Periods," *J. Struct. Eng.,*140, p. 04014073, 2014.

[20] Oñate E. and Zárate F., "Rotation-free triangular plate and shell elements," Int. *J. Num. Meth. in Eng.*, **47** 557-603 (2000).

[21] Florida International University, https://fiu.designsafe-ci.org/ (July 2017)
[22] Insurance Institute of Business and Home Safety https://disastersafety.org/ (July 2017).
[23] E. Simiu and R. H. Scanlan *Wind Effects on Structures* (3rd ed.), Hoboken: Wiley, pp. 533-534 (1996).
[24] A. Michalski, P.D. Kermel, E. Haug, R. Loehner, R. Wuechner, K.-U. Bletzinger "Validation of the computational fluid-structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. *J. Wind Eng. Ind. Aerod.* **99** 400-412 (2011).
[25] E. Simiu, A. L. Pintar, D. Duthinh and D. Yeo, "Wind Load Factors for Use in the Wind Tunnel Procedure," *J. Risk and Uncertainty in Eng. Systems* (in press).