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A Multiple Database-Enabled Design Module with Embedded Features of International Codes and Standards

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Abstract

This study presents the development of an advanced multiple database-enabled design module for high-rise buildings (DEDM-HR), which seamlessly pools databases of multiple high frequency base balance measurements from geographically dispersed locations and merges them together to expand the number of available building configurations for the preliminary design. This feature offers a new direction for the research and professional communities that can be utilized to efficiently pool multiple databases therefore expanding the capability of an individual database and improving the reliability of design estimates. This is demonstrated, in this study, by the unprecedented fusion of two major established databases, which facilitates interoperability. The DEDM-HR employs a cyberbased on-line framework designed with user-friendly/intuitive web interfaces for the convenient estimation of wind-induced responses in the alongwind, acrosswind and torsional directions with minimal user input. In addition, the DEDM-HR embeds a novel feature that allows the use of wind characteristics defined in a code/standard to be used in conjunction with the database. This supplements the provisions of a specific code/standard as in many cases guidance on the acrosswind and torsional response estimates is lacking. Through an example, results from several international codes and standards and the DEDM-HR with the embedded features are compared. This provision enhances the scope of the DEDM-HR in providing an alternative design tool with nested general provisions of various international codes and standards.

Keywords: Wind loads, High-rise buildings, High frequency base balance, Aerodynamics, Building design, Structural response, Building codes, Information technology (IT)

1. Introduction

Most codes and standards offer provisions for the wind load effects on structures with a focus primarily on the alongwind response. This has been facilitated by the introduction of the well-known quasi-steady and strip theories and the gust loading factor approach introduced by Davenport (1967) and later further refined over the years by several researches (e.g., Solari, 1993a, 1993b; Solari and Kareem, 1998; Zhou and Kareem, 2001). However, the failure of the basic assumptions in these theories and of the gust loading factor approach to capture the loading mechanisms in the acrosswind and torsional directions has precluded a formulation based on the first principles in these directions. Some codes and standards do provide limited guidelines on these aerodynamic loads; however, they are restricted to empirical expressions based on measured response of buildings tested in wind tunnels. Although these expressions are still valuable for assessing preliminary estimates of the response, their accuracy may not be consistent for different building shapes as often small changes in the shape result in major changes in the aerodynamic effects.

Alternatively, a popular methodology in wind design practice, i.e. a database-enabled design (DED) procedure, has been gradually gaining acceptance to overcome the aforementioned limitation pertaining to current codes and standards. The basic concept is to directly use wind tunnel-derived data for better response estimates in lieu of relying on code-specified load effects in which the overall accuracy may be compromised. A DED generally offers convenient meshing of a database with analysis software for low- to mid-rise and high-rise buildings. One example can be found in the form of open source MATLAB codes and manuals at the NIST website (http://www.itl.nist.gov/div898/winds/homepage.htm) for offline analyses (Whalen et al., 2000; Sadek and Simiu, 2002; Main and Fritz, 2006; Spence, 2009; Yeo, 2010). Another example, that overcomes the need for familiarity with the manipulations of MATLAB files, is given in the NatHaz aerodynamic loads database (NALD v. 1.0). This includes the web-based archiving and distribution of wind tunnel test data for the evaluation of the alongwind, acrosswind and torsional response of tall/high-rise buildings (Zhou et al., 2003). However, it still requires manual dynamic analyses based on random vibration theory for the preliminary design.

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To overcome the last step in NALD v. 1.0 involving off-line calculations, a more advanced DED approach for estimating the wind responses of tall/high-rise buildings has been presented with the help of recent developments in information technology (IT). This new paradigm offers attractive solutions with a concept of a cyberbased on-line on-the-fly analysis/design via user-friendly interfaces such as e-Wind (Cheng and Wang, 2004, http://windexpert.ce.tku.edu.tw), and NALD v. 2.0 (Kwon et al., 2005, 2008, http://aerodata.ce.nd.edu). This approach is particularly useful for those who may not be very familiar with the details of the random vibration-based dynamic analysis procedure generally used in conjunction with wind tunnel-driven data.

Although DED is a promising design procedure for the wind-induced response assessment in a better and more reliable way than conventional codes and standards, it requires a database of wind tunnel data, which often present a limited range of building shapes and configurations. To alleviate this limitation, this study introduces a new concept in DED, the database-enabled design module for high-rise buildings (DEDM-HR), which hosts multiple databases in collaboration with various research groups and efficiently utilizes them for enhancing the number of building shapes and configurations. In order to improve the user's accessibility, the DEDM-HR is implemented in a web-based on-line module with intuitive user-friendly interfaces for both the input and output in terms of familiar web-style forms and submission buttons that are nowadays commonly used in the design of web interfaces in most web services. Akin to the NALD v. 2.0, DEDM-HR utilizes databases of high frequency base balance (HFBB) measurements consisting of non-dimensional base moment spectra, that are successively adopted in the survivability and serviceability analysis/design by implementing the algorithms defined in NALD v. 2.0. In addition, with the success of NALD v. 2.0 as an alternative design procedure of the ASCE 7-05 and 7-10 (ASCE 2005, 2010), this study also investigates the possibility of expanding the application of the DEDM-HR to other international codes and standards. This feature will be particularly useful as the provisions for the estimation of the acrosswind and torsional response are in general very limited in most codes/standards.

2. DEDM-HR Framework

2.1. Theoretical background

The theory and procedure employed in DEDM-HR are basically similar to NALD v. 2.0 (Kwon et al., 2005, 2008) in which aerodynamic base moment/torque spectra obtained from HFBB experiments are utilized for evaluating the base moment/torque, the mean/background/resonant equivalent static wind loads (ESWL), the maximum displacements and the peak/RMS (root-mean-square) acceleration of a building. For the sake of completeness, the underlying theoretical background is briefly described here.

Assuming a stationary Gaussian process, the expected maximum base moment/torque response in the alongwind, acrosswind and torsional directions can be expressed as:

$$\hat{M} = \overline{M} + g \cdot \sigma_M \approx \overline{M} + \sqrt{M_B^2 + M_R^2} \tag{1}$$

$$= \overline{M} + \sqrt{(g_B \cdot \sigma_{CM} \cdot \overline{M'})^2 + \left(g_R \cdot \sigma_{CM} \cdot \overline{M'} \cdot \sqrt{\frac{\pi}{4\zeta_1} C_M(f_r)}\right)^2}$$

where, $\overline{M}$ = mean base moment that becomes zero in the acrosswind and torsional responses; M_B, M_R = peak background and resonant base moment or torque component, respectively; g, g_B, g_R = peak factors for total, background and resonant moments, respectively; σ_M, σ_{CM} = RMS of the fluctuating base moment/torque response and non-dimensional base moment/torque response coefficient ($=\sigma_M/\overline{M'}$), respectively; $\overline{M'}$ = reference moment or torque; ζ_1 = damping ratio of a building in the first mode; $C_M(f_r)$ = non-dimensional moment coefficient at $f_r(C_M(f_r) = f_r \cdot S_M(f_r)/\sigma_M^2)$; f_r = reduced frequency according to $f_1(f_r = f_1 B/\overline{U_H})$; f_1 = natural frequency of a building in the direction of motion; $S_M(f)$ = power spectral density (PSD) of the fluctuating base moment or torque response; f = frequency [Hz]; $\overline{U_H}$ = mean wind velocity at building height H. Since σ_{CM} and $C_M(f_r)$ are obtained from the HFBB experiments, the mean, background and resonant base moments/torques can be computed using the mechanical building properties.

Using Eq. (1), the equivalent static wind loads (ESWL) on a building can be computed by distributing the peak base moments to each floor in a similar fashion to how the base shear is distributed to each floor in earthquake engineering applications. Details can be found in Zhou et al. (2003), Kareem and Zhou (2003), and Kwon et al. (2008).

2.2. Multiple databases

One of the restrictions in the DED approach based on HFBB experiments is that only a limited number of data sets (such as terrain conditions, side ratio/aspect ratio etc.) may be available in a database, which may not cover the wide spectrum of cases desirable in design practice. To overcome such a limitation, and in alternative to the expansion of the database which may be precluded by limited resources, this study explores a scheme to merge in the background multiple databases from difference sources in the DEDM-HR. Although a centralized database system, which houses all databases on a central server, may be the simplest way to host multiple databases, the DEDM-HR utilizes a more advanced approach to link distributed databases, in which a central server communicates with multiple databases by utilizing advanced IT tools. This scheme is particularly attractive as each database and its server are in general characterized by their own unique environment, which requires either conformity or conversion of the data to meet the specific data formats. To achieve this goal, a PHP (personal hypertext preprocessor) library, XML-RPC (extensible markup language -

Table 1. Data sets in NatHaz and Tamkang databases

SR[1)]	0.20	0.25	0.33	0.40	0.50	0.67	1.00	1.50	2.00	2.50	3.00	4.00	5.00
NatHaz	-	-	O	-	O	O	O	O	O	-	O	-	-
NatHaz AR[2)]	-	-	4.62 5.77 6.93	-	3.77 4.71 5.66	3.27 4.08 4.90	4.00 5.00 6.00	3.27 4.08 4.90	3.77 4.71 5.66	-	4.62 5.77 6.93	-	-
Tamkang	O	O	O	O	O	O	O	O	O	O	O	O	O
Tamkang AR[3)]	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7	3~7

[1)]SR = side ratio (D/B); [2)]AR = aspect ratio $H/\sqrt{BD}$; [3)]ARs in the Tamkang database are 3, 4, 5, 6 and 7 for all SRs; Symbols 'O' and '-' = presence and absence of datasets in each database, respectively.

remote procedure call), is utilized through a combination of a library, a client and server PHP codes to transmit XML, where the XML contains meaningful information of HFBB data, over a typical web protocol, HTTP (hypertext transfer protocol). In this manner, this communication system is relatively independent of the web server configuration since in general the PHP, a web programming language, is compatible with any modern web server environment.

This concept is demonstrated in this study in the development of the DEDM-HR associated with two databases: one database is from the NatHaz Modeling Laboratory, of the University of Notre Dame USA, which is used in the NALD (Zhou et al., 2003; Kwon et al., 2005, 2008), and the other is from the Wind Engineering Research Center (WERC), the Tamkang University, Taiwan (Cheng and Wang, 2004; Cheng et al., 2007). The databases in the DEDM-HR are comprised of regularly shaped buildings involving square/rectangle cross-sections and do not include any unusual geometric irregularity. The NatHaz database consists of 7 cross-sectional shapes, 3 heights, 2 exposure categories and 3-dimensional loading, i.e., in the alongwind, acrosswind and torsional directions for each shape. The two exposure conditions in the NatHaz database are open ($\alpha = 0.16$, where α = power law exponent of the mean wind velocity profile) and urban ($\alpha = 0.35$), similar to the conditions of Exposure C in the ASCE 7-05 and 7-10 (open) and Exposure A in ASCE 7-98 (urban), respectively. On the other hand, the Tamkang database consists of 13 shapes, 5 heights and 3-dimensional loading for each shape. The Tamkang database has three exposures, i.e., open ($\alpha = 0.15$), suburban ($\alpha = 0.25$) and urban ($\alpha = 0.32$), which are close to Exposures C, B and A as defined in the ASCE standard (ASCE 7-98, 7-05 and 7-10), respectively. Although both the NatHaz and Tamkang databases have two common terrain conditions (Exposure A and C), the latter has a greater subdivision in the data sets, i.e., an additional terrain condition (Exposure B) and more test cases in shapes and heights, as shown in Table 1 for the overall side ratio (D/B) and aspect ratios ($H/\sqrt{BD}$) for both databases. The databases mainly consist of non-dimensional power spectral density [$C_M(f)$] and RMS base moment/torque coefficients (σ_{CM}) in three directions for each data set, which are utilized for estimating responses based on the theoretical approach given in Eq. (1). Detailed descriptions of the data sets and wind tunnel test conditions can be found in Kareem (1990), Kijewski and Kareem (1998), Zhou et al. (2003), Cheng and Wang (2004) and Cheng et al. (2007).

The reliability of the measured spectra in the databases has been established through verifications against data sets from other wind tunnel experiments (Kareem, 1990; Zhou et al., 2003; Lin et al., 2005; Kwon et al., 2008). In these studies, it was demonstrated that the NatHaz and Tamkang databases were in close agreement with the exception of a few cases. Some discrepancies in the response estimates may be attributed to slight differences in the inflow conditions at different wind tunnels, which are inevitable and to which the associated loads may be quite sensitive. Thus, such spectral comparisons are not further investigated in this paper.

2.3. Architecture of DEDM-HR

A schematic diagram of the DEDM-HR is illustrated in Fig. 1. To facilitate this web-based on-line system, various web-based tools/languages such as HTML/JavaScript, PHP, database management system (DBMS), e.g., MySQL and MSSQL etc., are utilized. This e-module is basically operated by a web server (e.g., Apache, MS IIS etc.), with two main processes, i.e., foreground and background processes.

The foreground process includes user-friendly interfaces for the selection of a desired analysis/design case, user inputs for wind properties such as basic wind speed, terrain roughness, building dimensions etc. as shown in Fig. 2 (user interface 1), additional interfaces for design inputs such as structural properties of a target building as shown in Fig. 3 (user interface 2), and display of analysis/design results for the user-specified building as shown in Fig. 4 (result interface). On the other hand, the background process involves server-side operations including database manipulations such as DB (database) query and computations performed implicitly in the DEDM-HR.

Since the DEDM-HR utilizes two databases, NatHaz and Tamkang, it is necessary to provide common features for data mining. Accordingly, the DEDM-HR uses a common criterion, i.e., the aspect ratio ($H/\sqrt{BD}$), with a fixed selection of cross-sectional shape as shown in Fig. 2, to seek out the best/most appropriate data sets existing in both the NatHaz and Tamkang databases. This operation

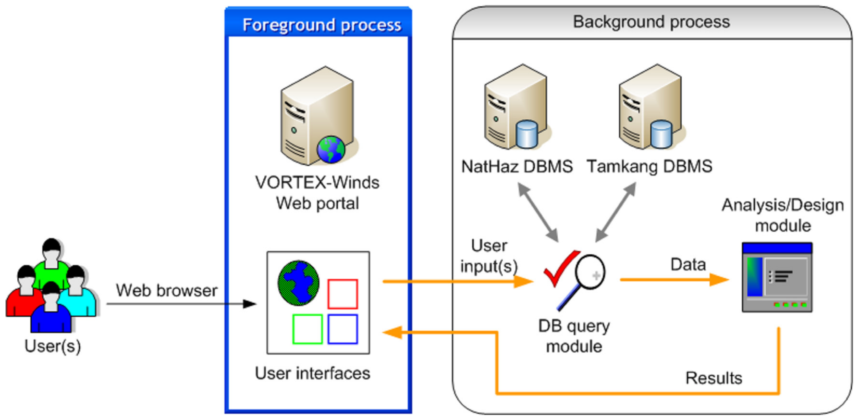


Figure 1. A schematic diagram of the DEDM-HR process.

occurs as a background process after the completion of the user interface 1 based on PHP codes in which the main server internally requests data from both databases based on user inputs, i.e., building's width (*B*), depth (*D*) and height (*H*). Both web servers hosting each database comply with the request, identify appropriate dataset(s) and send them to the main server in XML format. The user interface 2 gives the option of selecting the desired database, as shown in Fig. 3, if both databases have appropriate data sets. However, if only one database is available for the provided input data, then the choice shown is limited to only one database.

Akin to NALD v. 2.0 system (Kwon et al., 2008), MATLAB is employed as the major numerical calculation tool of the e-analysis/design in terms of a pre-programmed MATLAB code inside the main server in which such analysis/design is carried out after all inputs have been made (after user interface 2). Although the computational speed of MATLAB is known to be slower than other programming languages such as FORTRAN or C/C++, MATLAB offers some additional advantages such as abundant built-in functions for special computations and more sophisticated numerical schemes, easy modifications of the main codes without compiling, easy graphical representation such as graphs/charts, etc. In view of those advantages, the DEDM-HR adopted MATLAB as a computational framework. However, from the viewpoint of the web-based online implementation, it may be desirable to use more efficient programming languages such as Fortran, C/C++ etc. or converting MATLAB codes to C/C++ codes using MAT-

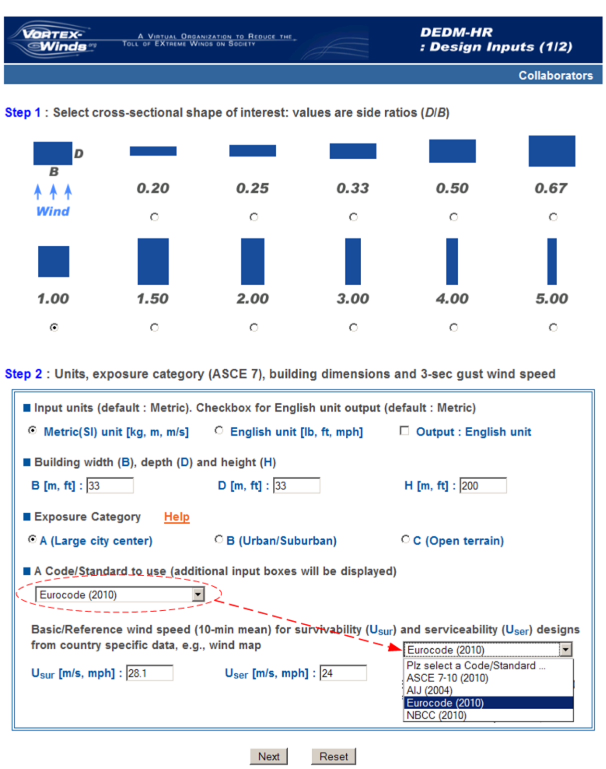


Figure 2. DEDM-HR user interface 1.

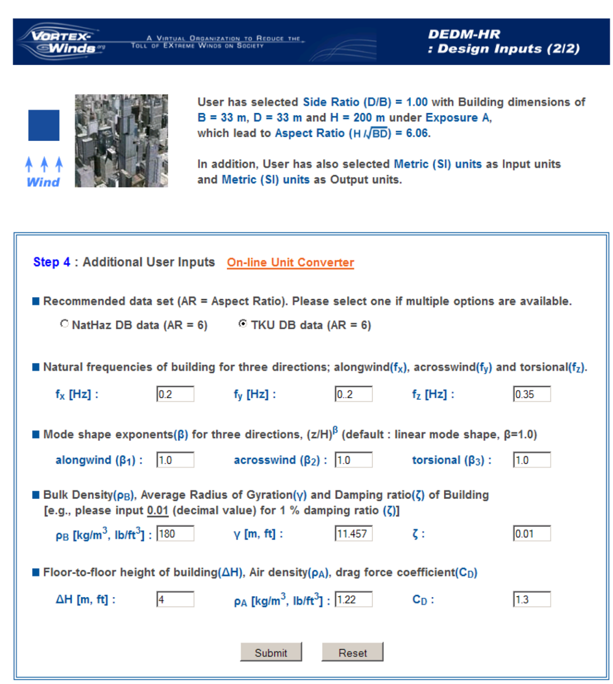
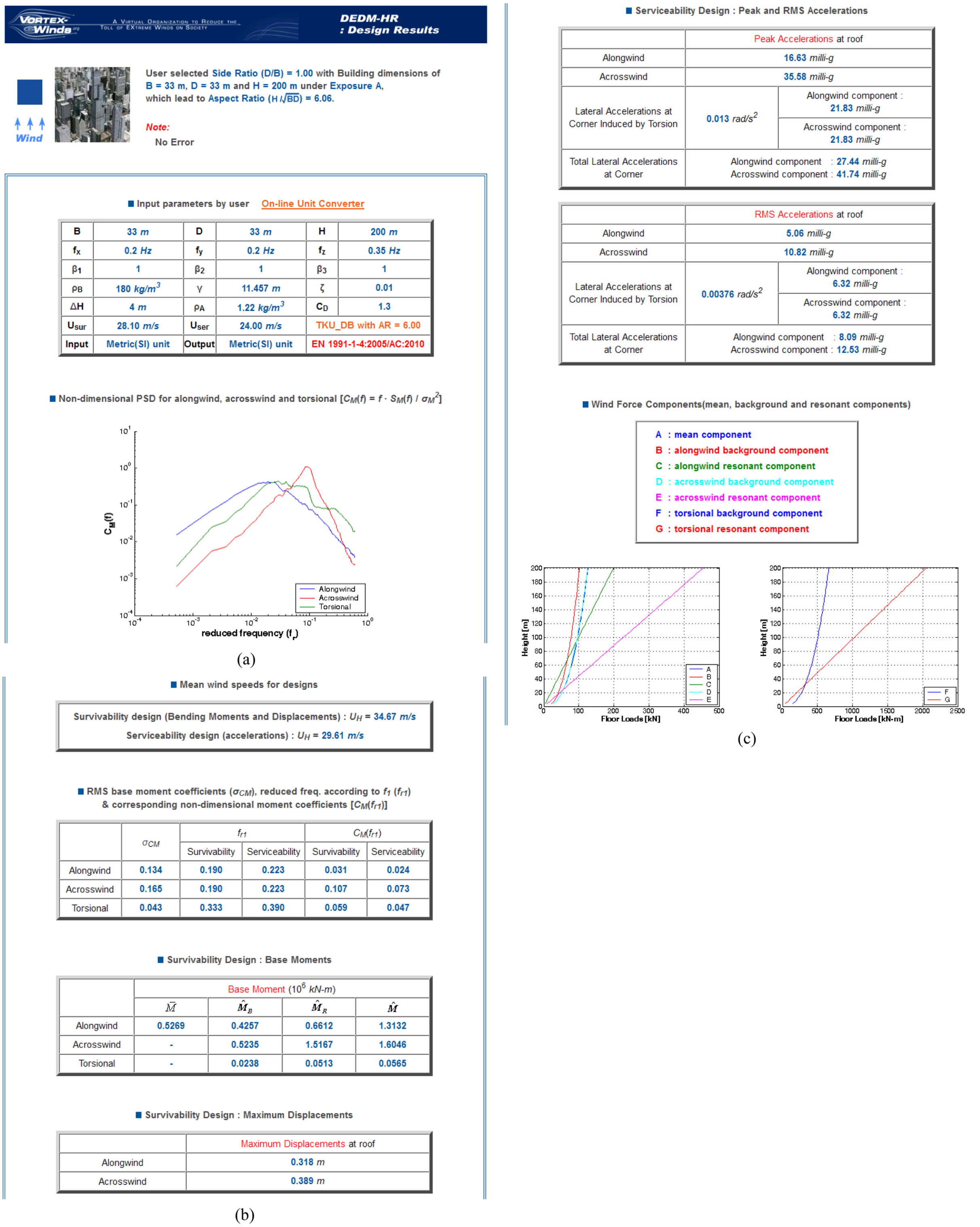


Figure 3. DEDM-HR user interface 2.



B	33 m	D	33 m	H	200 m
f_x	0.2 Hz	f_y	0.2 Hz	f_z	0.35 Hz
β_1	1	β_2	1	β_3	1
ρ_B	180 kg/m³	γ	11.457 m	ζ	0.01
ΔH	4 m	ρ_A	1.22 kg/m³	C_D	1.3
U_{sur}	28.10 m/s	U_{ser}	24.00 m/s	TKU_DB with AR = 6.00	
Input	Metric(SI) unit	Output	Metric(SI) unit	EN 1991-1-4:2005/AC:2010	

	σ_{CM}	f_{r1}		$C_M(f_{r1})$	
		Survivability	Serviceability	Survivability	Serviceability
Alongwind	0.134	0.190	0.223	0.031	0.024
Acrosswind	0.165	0.190	0.223	0.107	0.073
Torsional	0.043	0.333	0.390	0.059	0.047

	Base Moment (10^6 kN-m)			
	$\bar{M}$	$\hat{M}_B$	$\hat{M}_R$	$\hat{M}$
Alongwind	0.5269	0.4257	0.6612	1.3132
Acrosswind	-	0.5235	1.5167	1.6046
Torsional	-	0.0238	0.0513	0.0565

	Maximum Displacements at roof
Alongwind	0.318 m
Acrosswind	0.389 m

	Peak Accelerations at roof	
Alongwind	16.63 milli-g	
Acrosswind	35.58 milli-g	
Lateral Accelerations at Corner Induced by Torsion	0.013 rad/s²	Alongwind component : 21.83 milli-g; Acrosswind component : 21.83 milli-g
Total Lateral Accelerations at Corner	Alongwind component : 27.44 milli-g; Acrosswind component : 41.74 milli-g	

	RMS Accelerations at roof	
Alongwind	5.06 milli-g	
Acrosswind	10.82 milli-g	
Lateral Accelerations at Corner Induced by Torsion	0.00376 rad/s²	Alongwind component : 6.32 milli-g; Acrosswind component : 6.32 milli-g
Total Lateral Accelerations at Corner	Alongwind component : 8.09 milli-g; Acrosswind component : 12.53 milli-g	

Figure 4. DEDM-HR result interface: (a) user inputs and non-dimensional PSDs; (b) mean wind speeds and survivability design results; (c) serviceability design results and ESWLs.

LAB Coder (Mathworks 2013) in the case of time consuming computations such as complicated simulations.

After the main analysis is completed, the end user finds the following quantities displayed on the resulting interface (Fig. 4): non-dimensional base moment spectra, non-dimensional moment coefficients, mean/background/resonant/total base moments, displacements for survivability design and peak/RMS accelerations at the top of the building for serviceability design. These quantities are displayed for each of the three response components, i.e., alongwind, acrosswind and torsional directions. Finally, this is supplemented by plots of the mean, background and resonant components of ESWLs on the building.

3. International DEDM-HR: A Globalization Perspective

3.1. Motivation for developing international DEDM-HR

For the estimation of alongwind load effects on flexible structures like tall buildings, most international codes and standards have widely adopted a common framework, i.e., the random vibration-based gust loading factor approach (Davenport, 1967), even if the various parameters are defined differently in each code/standard. In the case of acrosswind and torsional response, the complicated aerodynamic interactions are not easily captured by the quasi-steady theory-based formulations which are, for the alongwind response, subsequently translated into simplified expressions. This is reflected in the limited number of codes/standards that offer guidelines for the acrosswind and torsional directions (Zhou et al., 2002; Tamura et al., 2005).

A fusion of a code/standard and a DED procedure is an attractive feature to supplement the provision of a specific code or standard. To realistically accomplish this, it is necessary to identify key parameters among many variables defined in a code/standard. Previous studies have noted that differences in the definitions of wind field characteristics, including mean wind velocity profile, turbulence intensity profile, wind spectrum, turbulence length scale and wind correlation structure, among different codes/standards were the primary contributors to the scatter in the predicted response quantities (Zhou et al., 2002; Tamura et al., 2005). More recently, Bashor and Kareem (2009) reported that overall loads among several codes and standards are reasonably consistent, while significant discrepancies are apparent in the comparison of the intermediate parameters. They also noted that the parameters contributing to the more important differences in the resulting wind loads were those associated with wind characteristics such as the basic wind velocity and its profile.

These observations and the inclusion of the NALD e-module in the Commentary of ASCE 7-05 and 7-10 have provided the motivation to establish a globalized framework of DEDM-HR, namely international DEDM-HR. The basic concept behind the international DEDM-HR is to implicitly embed the wind characteristics as defined in international code/standard in the database. Utilizing these wind characteristics in conjunction with the main analysis/design schemes used in DEDM-HR, an alternative design procedure for assessing the wind load effects on high-rise buildings based on a specific code or standard is offered. An added advantage of this approach will include the addition, as a supplement to the code/standard, of a provision for estimating the loading effects in the acrosswind and torsional directions. This added feature promises to enhance what is typically offered by a current code/standard. Note that the reliability of the international DEDM-HR framework can be further improved if HFBB database(s) consistent with code-specified inflow conditions can be couched in this framework.

3.2. Comparison of wind characteristics in international codes and standards

To develop the international DEDM-HR, it is first necessary to examine the wind characteristics specified in selected codes and standards. Initially, six major international codes and standards are chosen in this study: the American Society of Civil Engineers' Minimum Design Loads for Buildings and Other Structures (ASCE, ASCE 2010), the Australian and New Zealand Standard (AS/NZ, Joint Technical Committee 2011), the Architectural Institute of Japan Recommendations (AIJ, AIJ 2004), the National Building Code of Canada (NBCC, NRC2010), the European Standard (Eurocode, CEN 2010) and the International Organization for Standardization Standard (ISO, ISO 2009). Note that the Eurocode provides two different procedures in Appendix B and C, and ISO also provides two procedures for determining loads such as peak and mean responses. Based on these codes and standards, some parameters in the wind characteristics such as averaging time, profiles of wind velocity and turbulence intensity and peak factors, which may significantly impact the wind-induced response estimates, are compared in the following. The exposure categories in the selected codes and standards are listed in Table 2 and compared to the exposures considered in the DEDM-HR. The same symbols used in the codes/standards are adopted. Note that the basic wind velocity is commonly defined at a height of 10 m in an open terrain, which corresponds to Exposure C of the DEDM-HR.

The wind velocity profile in codes and standards is described by either a power or a logarithmic law, in particular, AS/NZ, Eurocode and ISO use a logarithmic law, whereas the others use a power law. The power law may be generalized in the following form (Zhou et al., 2002):

Table 2. Comparison of exposure categories among international codes and standards

DEDM-HR	ASCE7	AS/NZ	AIJ	NBCC	Eurocode	ISO
A	A*	4	IV	C	IV	4
B	B	3	III	B	III	3
C	C	2	II	A	II	2

*Although ASCE A is no longer defined since ASCE 7-02, it is used in this analysis for comparison purposes.

Table 3. Power law coefficients in the six codes/standards

DEDM-HR	ASCE7		AS/NZ*		AIJ		NBCC		Eurocode*		ISO*	
	b	α	b	α	b	α	b	α	b	α	b	α
A	0.30	0.333	0.306	0.271	0.58	0.27	0.426	0.36	0.69	0.194	0.33	0.28
B	0.45	0.250	0.460	0.20	0.79	0.20	0.666	0.25	0.86	0.162	0.52	0.20
C	0.65	0.154	0.605	0.15	1.00	0.15	1.000	0.14	1.10	0.12	0.68	0.15

*fitted from logarithmic law profile.

Table 4. Averaging times and reference heights

	ASCE7	AS/NZ	AIJ	NBCC	Eurocode	ISO*
Basic wind velocity (V_0)	3-sec	3-sec	10-min	1-hr	10-min	3-s 10-min
Wind-induced response	1-hr	10-min	10-min	1-hr	10-min	10-min

*ISO provides two procedures for determining loads: one for peak response and one for mean response.

$$V(z) = b\left(\frac{z}{10}\right)^{\alpha} V_0 \qquad (2)$$

where α and b are terrain variables, z is the height of interest, and V_0 is the basic/reference wind velocity. Note that, since the DEDM-HR procedure is based on the power law profile, the logarithmic law profiles in AS/NZ, Eurocode and ISO are fitted to Eq. (2). All profile variables summarized in Table 3 are based on the averaging time for the wind-induced response calculation. Note that averaging times for the basic wind velocity and wind-induced response may vary among and within codes and standards because some utilize 3-sec gust speed (ASCE, AS/NZ and ISO) instead of the mean wind speed (10-min or 1-hr) in the basic/reference wind velocity, while a much longer averaging time is generally used for the calculation of wind-induced responses such as 10-min or 1-hr (Table 4). The averaging time of the wind-induced response estimation affects the peak factors, which are mainly a function of the averaging time and the natural frequency of a tall building.

To compare profiles consistently, it is important to compensate for the different averaging times in the definition of the basic wind velocity of the various codes and standards. Thus, non-dimensional velocity profiles [$V_{non}(z)$] are evaluated based on their respective averaging times used for the calculation of wind-induced responses, therefore either 1-hr (ASCE and NBCC) or 10-min (others) as described in Table 4, i.e., $V_{non}(z) = V(z)/V_{0(10\text{-}min\ or\ 1\text{-}hr)}$. This study utilizes, for compensating the differences in averaging times, the relationship developed by Durst and reported in graphical form (ASCE 2005): $V_{0(3\text{-}sec)} = G_{v(10\text{-}min)}V_{0(10\text{-}min)} = G_{v(1\text{-}hr)}V_{0(1\text{-}hr)}$, where $G_{v(10\text{-}min)} = 1.42$ and $G_{v(1\text{-}hr)} = 1.51$. As shown in Fig. 5, the codes and standards have similar profiles, with the minor discrepancies that may exist being attributed to the differences in the averaging time (10-min and 1-hr). However, it is noticeable that ISO in Exposure A, and AS/NZ for all three exposures present profiles somewhat different from the others, which may strongly affect the wind loads. In addition, the urban profile (Exposure A) leads to the most divergent results as compared to the other exposures. The turbulence intensity profiles are also compared in Fig. 6. In this case as well some discrepancies are observed, especially for the urban exposure category (Exposure A). It can also be observed that, in exposures B and C, the turbulence intensity profiles used in both the NatHaz and the Tamkang databases have a smaller vertical range compared to the profiles given by other codes and standards, which could possibly result in some discrepancies with the code-based response estimates.

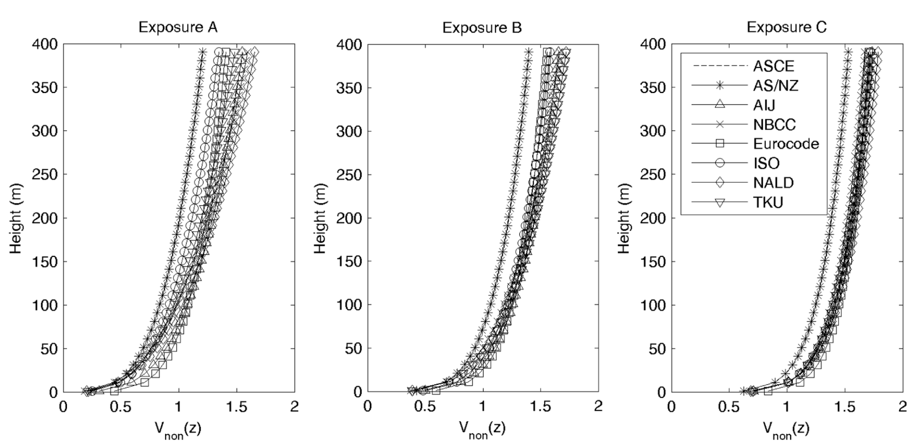


Figure 5. Wind velocity profiles in Exposure A, B and C.

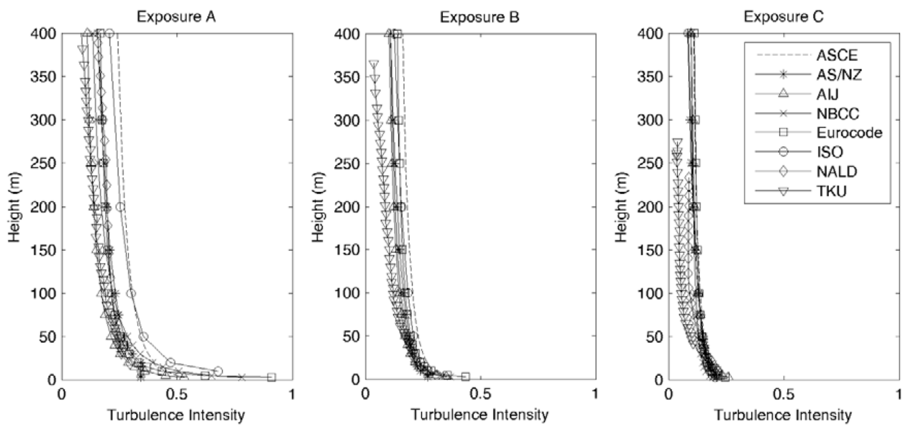


Figure 6. Turbulence intensity profiles in Exposure A, B and C.

Finally, another parameter considered in the international DEDM-HR is the peak factor. As shown in Eq. (1), wind loading effects in the gust loading factor approach are governed by g_B and g_R (the peak factors for the background and resonant responses, respectively). The peak factor describes the fluctuating response by defining the ratio of the maximum value to the standard deviation. A well-known expression for the peak factor, derived under the assumption of a Gaussian parent distribution, is given by (Davenport, 1967):

$$g=\sqrt{2\ln(\nu T)}+\frac{0.5772}{\sqrt{2\ln(\nu T)}} \quad (3)$$

where T is the averaging time (sec) and ν is the up-crossing frequency, which, can be simply approximated with the fundamental frequency (Hz) of the building or, according to some codes, $\nu=f_1C$, where C is a function of the background and resonant response. In the DEDM-HR, the factor C is assumed to be unity for convenience in implementation, since it has been demonstrated that it does not significantly affect the peak factor (Bashor, 2010). All codes and standards essentially utilize Eq. (3) for the resonant peak factor (g_R). ASCE, AS/NZ and ISO use a constant value for the background peak factor (g_B), while others simply take g_B equal to g_R. Typically, peak factors are between 3 and 4 assuming a Gaussian parent distribution (Zhou et al., 2002). A summary of the peak factors adopted in the various codes and standards is provided in Table 5.

3.3. Implementation of international DEDM-HR

In order to adopt international codes and standards in the DEDM-HR, a user selection of the code/standard is introduced in a pull-down menu shown in Fig. 2. If a user selects a specific code/standard, then the corresponding input box for the basic wind velocity automatically appears below the menu, which most codes and standards provide through regional wind maps for survivability and serviceability designs. Two input boxes for the basic wind velocities are generally shown, corresponding to the survivability and the serviceability return periods as defined by the code/standard. In the case of ASCE 7, only one input box for the basic wind speed (3-sec gust) for the survivability design is provided as ASCE 7 offers an internal conversion factor for different return periods. The other parameters such as the averaging time, wind profile vari-

Table 5. Comparison of peak factors

	g_R	g_B	T	ν
ASCE7	$g=\sqrt{2ln(\nu T)}+\frac{0.577}{\sqrt{2ln(\nu T)}}$	3.4	3600	f_1
AS/NZ	$g=\sqrt{2ln(\nu T)}$	3.7	600	f_1
AIJ	$g=\sqrt{2ln(\nu T)+1.2}$	g_R	600	f_1C
NBCC	$g=\sqrt{2ln(\nu T)}+\frac{0.577}{\sqrt{2ln(\nu T)}}$	g_R	3600	f_1C
Eurocode	$g=\sqrt{2ln(\nu T)}+\frac{0.6}{\sqrt{2ln(\nu T)}}$	g_R	600	f_1C
ISO	$g=\sqrt{2ln(\nu T)}+\frac{0.577}{\sqrt{2ln(\nu T)}}$	3.4	600	f_1

ables [b and α in Eq. (2)], background and resonant peak factors for each code and standard are included in the DEDM-HR based on Tables 2-5, thus a user only needs to input basic/reference wind velocities for both survivability and serviceability designs. Note that the effects of topography, directionality, building importance and other factors are currently not included in the DEDM-HR, which can be added in a subsequent update.

4. Comparison of International DEDM-HR and Codes/standards

In this section the international DEDM-HR and the various codes and standards are compared considering survivability design requirements in the alongwind and acrosswind directions (base shears and base moments), as well as serviceability design requirements (accelerations). To this end, an example building is considered whose characteristics are: width B = 33 m; depth D = 33 m; height H = 200 m; natural frequencies in alongwind and acrosswind directions, $f_x = f_y$ = 0.2 Hz, respectively; linear mode shapes; building bulk density ρ_B = 180 kg/m^3; damping ratio ζ = 0.01; interstory height ΔH = 4 m; air density ρ_A = 1.22 kg/m^3; drag force coefficient C_D = 1.3. The basic wind velocities (V_0) are assumed to be 40 m/s (3-sec) for survivability design and 34 m/s (3-sec) for serviceability design (the compensation for different averaging times is carried out through the previously mentioned Durst curve reported in ASCE 2005). The building is assumed to be located in an urban and open area (Exposure A and C). The building model in the database which best approximates the case study is characterized by side ratio (D/B) = 1 (square cross-section) and aspect ratio ($H/\sqrt{BD}$) = 6.06. Note that the Eurocode does not provide windward and leeward pressure coefficients when H/D > 5. In this case, they offer to use force coefficient (C_f) for estimating total wind loading and it is about 1.45 considering the example building in this study (Section 7 in the Eurocode).

The survivability design results in the alongwind direction are presented in Table 6 for Exposure A and in Table 7 for Exposure C. In Exposure A, the most noticeable discrepancies in both the base shear and moment are found in AS/NZ and ISO, which may be due to the noteworthy difference in the wind profiles between the standards and the databases observed in the Fig. 5. On the other hand, ISO based results in Exposure C are close to DEDM-HR because the ISO wind profile in this exposure is close to the one in DEDM-HR. These trends agree with the observations from previous studies (Zhou et al., 2002; Tamura et al., 2005; Bashor and Kareem, 2009) that the differences in the wind profiles are one of the primary contributors to the scatter in the predicted response quantities. It is surprising that AS/NZ in Exposure C gives similar values to DEDM-HR despite the discrepancy in the wind profiles. This could possibly be explained by the fact that in the latest version of the AS/NZ (Joint Technical Committee, 2011) the combination factor applied to the external pressure, $K_{c,e}$, is defined to be equal to 0.9, whereas in the previous version (SAA 2002) it was set equal to 1.0. This new value of $K_{c,e}$ leads to a reduction in the overall alongwind

Table 6. Alongwind survivability results in Exposure A

	ASCE7	AS/NZ	AIJ	NBCC	Eurocode		ISO	
					B	C	Peak	Mean
V_0 (m/s)	40.0	40.0	28.1	26.4	28.1		40.0	28.1
g_R	3.787	3.094	3.210	3.755	3.207		3.281	3.281
Code V_{base} (MN)	9.99	8.73	11.98	9.86	13.33	13.88	10.40	9.02
NatHaz V_{base}	8.80	5.82	10.89	9.06	11.00		7.23	
Tamkang V_{base}	9.28	6.15	11.74	9.65	11.48		7.76	
Code M_{base} (MN-m)	1,104	957.0	1,341	1,145	1,506	1,568	1,251	1,178
NatHaz M_{base}	1,111	711.2	1,345	1,150	1,319		891.7	
Tamkang M_{base}	1,172	750.7	1,452	1,226	1,374		958.4	

*V_{base} = base shear; M_{base} = base moment.

Table 7. Alongwind survivability results in Exposure C

	ASCE7	AS/NZ	AIJ	NBCC	Eurocode		ISO	
					B	C	Peak	Mean
V_0 (m/s)	40.0	40.0	28.1	26.4	28.1		40.0	28.1
g_R	3.787	3.094	3.229	3.765	3.232		3.281	3.281
Code V_{base} (MN)	14.93	12.61	17.97	15.94	19.85	20.62	14.74	14.15
NatHaz V_{base}	14.19	11.29	15.27	13.71	16.84		14.31	
Tamkang V_{base}	14.38	11.35	15.54	13.86	17.12		14.56	
Code M_{base} (MN-m)	1,599	1,336	1,956	1,736	2,168	2,253	1,667	1,703
NatHaz M_{base}	1,705	1,341	1,821	1,635	1,973		1,705	
Tamkang M_{base}	1,726	1,345	1,853	1,650	2,006		1,733	

loads and accelerations in the AS/NZ, while DEDM-HR did not consider this reduction. Thus, for this case study, the effect of the discrepancy between the wind profiles of AS/NZ and the databases may be compensated by the reduction factor in Exposure C. Some discrepancies of the base shear and moment in the Eurocode and international DEDM-HR may be partly attributed to a unique definition of the windward velocity pressure profile along the height in the Eurocode when $H > 2B$. The Eurocode considers the profile as multiple parts, comprising: a lower part extending upwards from the ground by a height equal to B; an upper part extending downwards from the top by a height equal to B and a middle region, between the upper and lower parts, which may be divided into horizontal strips with a height (CEN, 2010). Despite the differences in the wind response expressions for the alongwind direction adopted in each code and standard, the overall comparison between the results obtained through the various codes/standards and those obtained by DEDM-HR is quite good, especially when wind velocity profiles are similar to those in the databases such as ASCE7, AIJ, NBC and Eurocode.

Only AS/NZ, AIJ and ISO offer provisions for the acrosswind survivability design (Table 8), however, the expressions provided by ISO and AIJ are almost the same. It is observed that, unlike the alongwind case, inconsistent results among codes/standards and DEDM-HR are found. Such differences are more pronounced in Exposure C than in Exposure A. This may be explained considering that inflow conditions with lower turbulence intensity result in higher loads. Similar observations hold for the serviceability design case as shown in Tables 9 and 10 for Exposure A and C, respectively. In this case ISO is not considered because it does not provide any provision for the estimate of accelerations. It can be seen that, also in this case, the results obtained by AS/NZ are characterized by large discrepancies with respect to the other codes and standards, especially for Exposure A. Also, in general, Exposure C results exhibit a larger spread than those seen for Exposure A with the acrosswind results showing an even greater scatter than the alongwind results. It is observed that the AIJ acrosswind results generally provide responses higher than the responses given by the DEDM-HR. This may be attributed to the fact that the empirical expressions for the non-dimensional PSD provided by AIJ, especially in Exposure C, are relatively larger than those in the NatHaz database around the reduced frequency of interest, i.e., in the high frequency region, as observed by Kwon et al. (2008). Therefore, it is not surprising to see some discrepancies in the acrosswind results between AIJ and DEDM-HR. In general, the results obtained from the NatHaz and the Tamkang databases are mostly in good agreement with each other; the slight discrepancies which can be observed between the two may be explained with the slight differences in the test conditions between the two databases such as wind profile, turbulent intensity, etc.

The trends observed from the results of both survivability and serviceability conditions may be explained by the following points: a) wake-induced effects may be relevant in the case study building considering its side ratio/aspect ratio, which has led most codes and standards to recommend, in such cases, the use of wind tunnel tests in conjunction with code-specified estimates; b) although some codes and standards offer approximate expressions for the acrosswind responses based on wind tunnel measurements, such simplified versions can only offer a rough estimate due to the limited test results utilized. Some codes/standards allow interpolation, which may not always be accurate since aerodynamic effects in the acrosswind direction are in general more prevalent and may not be amenable to simple interpolation or extrapolation.

In light of these concerns, the use of DEDM-HR as an alternative and supplementary procedure in conjunction with the input recommendations of the codes and standards is particularly valuable. While DEDM-HR adds a direct input from wind tunnel tests, but in its current form does not include any aeroelastic (motion-induced) effects, which cannot be captured by HFBB tests. The possibility of including this information is however being explored based on the availability of tests recently carried out at the Bridge Engineering Department, Tongji University, PRC (Tongji University, 2012).

In closing, DEDM-HR was designed to house four international codes and standards, ASCE, AIJ, NBCC and Eurocode. Based on the preceding observations, the AS/NZ and ISO have been excluded at this stage because of the

Table 8. Acrosswind survivability results in Exposure A and C

	Exposure A				Exposure C			
	AS/NZ	AIJ	ISO Peak	ISO Mean	AS/NZ	AIJ	ISO Peak	ISO Mean
g_R	3.094	3.283	3.281	3.281	3.094	3.283	3.281	3.281
Code V_{base} (MN)	9.52	14.32	6.99	6.52	15.90	27.52	21.84	21.96
NatHaz V_{base}	4.77	12.81	7.04		10.18	16.47	14.84	
Tamkang V_{base}	5.92	14.47	8.41		10.78	17.61	15.80	
Code M_{base} (MN-m)	1,283	1,929	999.0	951.9	2,141	3,706	3,021	3,087
NatHaz M_{base}	601.5	1,652	891.7		1,259	2,084	1,868	
Tamkang M_{base}	750.4	1,866	1,079		1,334	2,229	1,991	

Table 9. Alongwind and acrosswind serviceability results in Exposure A

	ASCE7	AS/NZ	AIJ	NBCC	Eurocode	
					B	C
Alongwind						
V_0 (m/s)	34.0	34.0	24.0	22.5	24.0	24.0
g_R	3.787	3.094	3.210	3.755	3.207	3.207
Code $\sigma_{\ddot{x}}$ (milli-g)	3.44	2.79	3.96	-	5.06	6.02
NatHaz $\sigma_{\ddot{x}}$	3.68	2.50	5.34	4.10	4.60	
Tamkang $\sigma_{\ddot{x}}$	3.90	2.44	5.93	4.23	5.06	
Code $\hat{\ddot{x}}$ (milli-g)	13.03	8.65	12.72	-	16.11	19.19
NatHaz $\hat{\ddot{x}}$	13.92	7.74	17.54	15.51	15.11	
Tamkang $\hat{\ddot{x}}$	14.77	7.54	19.45	16.00	16.63	
Acrosswind						
Code $\sigma_{\ddot{y}}$ (milli-g)	-	9.85	12.75	7.19	-	-
NatHaz $\sigma_{\ddot{y}}$	6.23	3.81	10.84	6.95	8.59	
Tamkang $\sigma_{\ddot{y}}$	8.03	4.47	12.89	9.06	10.82	
Code $\hat{\ddot{y}}$ (milli-g)	-	30.48	40.92	26.92	-	-
NatHaz $\hat{\ddot{y}}$	23.60	11.80	35.59	26.31	28.26	
Tamkang $\hat{\ddot{y}}$	30.41	13.84	42.32	34.31	35.58	

* $\sigma_{\ddot{x}}$, $\sigma_{\ddot{y}}$ = RMS accelerations; $\hat{\ddot{x}}$, $\hat{\ddot{y}}$ = peak accelerations at building height.

Table 10. Alongwind and acrosswind serviceability results in Exposure C

	ASCE7	AS/NZ	AIJ	NBCC	Eurocode	
					B	C
Alongwind						
V_0 (m/s)	34.0	34.0	24.0	22.5	24.0	24.0
g_R	3.787	3.094	3.229	3.765	3.232	3.229
Code $\sigma_{\ddot{x}}$ (milli-g)	3.85	3.75	6.06	-	6.94	8.04
NatHaz $\sigma_{\ddot{x}}$	6.22	4.47	7.98	5.91	8.08	
Tamkang $\sigma_{\ddot{x}}$	7.22	5.82	7.98	7.06	8.04	
Code $\hat{\ddot{x}}$ (milli-g)	14.58	11.60	19.57	-	22.25	25.86
NatHaz $\hat{\ddot{x}}$	23.57	13.83	26.20	22.37	26.57	
Tamkang $\hat{\ddot{x}}$	27.35	18.01	26.20	26.75	26.45	
Acrosswind						
Code $\sigma_{\ddot{y}}$ (milli-g)	-	13.20	24.11	13.67	-	-
NatHaz $\sigma_{\ddot{y}}$	10.97	8.79	13.78	10.60	13.98	
Tamkang $\sigma_{\ddot{y}}$	11.13	9.09	14.52	10.73	14.81	
Code $\hat{\ddot{y}}$ (milli-g)	-	40.84	77.81	51.34	-	-
NatHaz $\hat{\ddot{y}}$	41.56	27.19	45.24	40.15	45.98	
Tamkang $\hat{\ddot{y}}$	42.14	28.14	47.67	40.64	48.68	

rather large discrepancies observed between their wind velocity profiles (Fig. 5) and those employed in the databases. Better estimates for AS/NZ and ISO and even for other codes/standards may be accomplished if code-specified wind tunnel data sets are included in the DEDM-HR, i.e., the test conditions for the HFBB experiments that reflect wind velocity and turbulence intensity profiles as defined in the respective codes and standards.

5. Concluding Remarks

This paper presents an advanced multiple database-enabled design module for high-rise buildings, DEDM-HR, which features a fusion of data from geographically dispersed databases populated by a suite of building shapes and heights. This feature offers a seamless interoperability between databases. It is currently hosted as an e-module on the website of the virtual organization VORTEX-Winds available at https://vortex-winds.org/. The DEDM-HR offers web-based on-line on-the-fly preliminary design for wind loading effects on buildings in the alongwind, acrosswind and torsional directions. The database-enabled design is further enriched by embedding wind characteristics defined in a number of international codes and standards to serve as input. Accordingly, DEDM-HR offers an alternative and supplementary design procedure in conjunction with the recommendations of the respective codes/standards. It is envisioned that with the expandability of DEDM-HR to accommodate multiple databases, additional HFBB databases, with proper code-specified wind characteristics such as exposure conditions, profiles of wind velocity and turbulence intensity etc., can be couched in the DEDM-HR. Alternatively, it is suggested that those standards that show noteworthy departure from generally accepted conditions should re-evaluate their recommendations. It is envisaged that, starting with the current contribution as the initial attempt, refinements along the lines of those suggested in this study will enhance DEDM-HR, ultimately making it a comprehensive and invaluable design procedure with the expedience of international codes and standards to fully meet the escalating global design demands.

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