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Database-assisted design for wind: basic concepts and software development

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Abstract

Standard provisions for wind loads on buildings have traditionally been based on summary tables and/or plots suitable for slide-rule calculations. The accuracy in the definition of wind loads inherent in such tables and plots is far lower than that inherent in current methods for stress computation. Advances in computational power now make it possible to reduce this discrepancy and achieve structural designs for wind that are significantly safer and more economical than current designs. This is true both for routine, low-rise structures and for flexible structures experiencing significant dynamic effects. In this paper, we present the concept of database-assisted design (DAD) along with a discussion of the application software Wind Load Design Environment, a user-friendly tool for designers and code writers that employs the DAD approach. The DAD approach entails the use of large databases of aerodynamic pressures, the optional use of databases of directional extreme wind speeds, and the use of structural information needed for the description of linear or nonlinear structural behavior. We present progress achieved to date, describe current efforts and future needs, and discuss the implications of DAD for reliability-based design and performance-based standards development.

Keywords: Building technology; Database-assisted design; Building codes; Structural engineering; Wind engineering; Wind loads

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1. Introduction

Modern computational capabilities have enabled civil engineers to analyze intricate structural systems with superior accuracy and produce previously impossible designs, while computer-aided design tools have greatly enhanced the efficiency and effectiveness of design practices. For wind load specification, however, standards contain significant inconsistencies with respect to risk and do not include sufficient information allowing designers to account realistically and comprehensively for spatial and temporal wind loading features. They still largely rely on reductive tables and plots developed essentially "by eye" from the inspection of large amounts of wind-tunnel data. Several researchers [1–3] have identified examples of risk inconsistencies for wind loads and load effects based on the use of conventional standard provisions.

The need for improving the performance of codes and standards has frequently been cited as a priority for all areas of hazard mitigation, including wind hazard mitigation [4,5]. In [6], improving the information content of wind load standards was identified as a key component of an overall strategy to reduce wind-associated losses in the next 10 years. Clearly, significant progress in design for wind loads will occur only when a means for delivering improved wind information in an effective manner can be developed.

To help overcome current deficiencies in wind specification, standards such as ASCE 7-98 [7] (Section 6.6.2, item 3) allow for the use of supplemental information in the form of databases of wind-tunnel tests. The intent is to provide a much more complete picture of the wind environment and the resulting loads that would be exerted on a structure. This approach requires storing and effectively processing large amounts of aerodynamic data. For example, in [8], a 1.0 min wind-tunnel test (approximately equivalent to a 1.0 h full-scale test) of a single design case for 37 wind directions produced about 1.8 Gbytes of data. In addition, the demands of the experimental system and not those of the end user commonly govern the organization of the aerodynamic data. It is therefore necessary to provide a mechanism for dealing with this information that is fast, efficient, and easy to use by the practicing engineer.

The term "database-assisted design" (DAD) has been coined [9] to describe the process of using powerful computer applications to define wind loads via libraries of test results in combination with design and analysis methods. Recent efforts have been centered on the development of a first generation DAD application called WiLDE-LRS—Wind Load Design Environment for Low-Rise Structures [10]. This Matlab®-based software processes aerodynamic pressure data from wind-tunnel test databases along with specific building and frame design information to produce time histories of wind load effects in the supporting frames and other components. It can easily be extended to incorporate other analysis modules or interact with powerful analysis programs, and it can output a wide range of results. It has the ability to integrate current or future developments in wind engineering, structural dynamics, nonlinear mechanics, structural reliability, and computational fluid dynamics (CFD). Examples of such integration are provided in this paper. WiLDE represents a vision of a future DAD tool that will include comprehensive databases and use them to estimate wind effects realistically in a user-friendly environment.

In this paper, we discuss the DAD concept in detail and illustrate its impact for a number of selected tasks. In Section 2 we provide background information on the concepts and developments related to DAD. Previous work is discussed and specific needs are identified. Section 3 presents a description of WiLDE along with an overview of its organization. In Section 4, the analysis of a variety of wind loading problems via WiLDE is described, showing how the DAD approach can lead to a significant improvement in the understanding of wind effects from the practical design and reliability-based codification viewpoints. These can include wind direction effects, nonlinear effects (e.g., local buckling), and statistical information developed for design and structural reliability estimation purposes. Finally, Section 5 presents concluding statements on DAD and indicates future directions for research.

2. Background on DAD

The DAD concept has its roots in the field of standards representation and processing—for a history see [11]. Most efforts in this field have been concerned with the implementation of generic standard processing systems that perform automatic code checking on formal models of standards, thus separating the processor from the specific design situation [12]. Several strategies for representing provisions in a computational form have been advocated, including the use of decision tables [13], logic programming [14], predicate calculus [15], object-oriented techniques [16,17], and most recently, distributed and web-based architectures [18]. Such methods are best suited for dealing with the types of provisions that can be modeled as text-based "facts" or "rules" to which first-order logic can be applied. While important, these models of computer-based standards do not address the representation of complex design information and do not deal effectively with the problems associated with wind load standards provisions.

Expert systems have been proposed as a means for electronically conveying design information for complex systems, and applications specific to wind loading have been developed [19]. A rule-based expert system WINDLOADER has been adopted to represent a version of the Australian standard for wind loads [20]. This system guides the user through the code provisions, reducing errors in interpretation. Knowledge-based systems for describing the wind environment around high-rise buildings have been devised [21–23]. Expert systems for more general wind load design situations have also been investigated [24,25]. While similar in spirit to DAD, expert systems are primarily intended to provide guidance to designers dealing with unfamiliar wind loading situations. They are not per se concerned with improving the information content of relevant wind codes and standards, although they do bring large databases of information to bear on their respective problems. Rather, expert systems stress accessibility of the information to the general designer, and they will often introduce their own simplifications and reductive assumptions into the wind analysis in order to expedite communication of this information. Thus, expert systems and DAD applications have different (though complementary) goals: expert systems seek to improve the transmission of existing wind design information, while DAD tools seek to improve the wind information being transmitted. Both approaches have a role to play in improving the overall practice of wind design.

In recent years, the National Institute of Standards and Technology (NIST) has pursued a number of projects related to the use of computers and databases to improve wind-loading provisions. The initial discussion in [26] dealt with both questions of standards representation and the creation of required knowledge bases and procedures to make use of them. The authors of [27] produced an electronic version of the wind loading provisions of ASCE 7-95 [28]. While this allowed users to accurately determine wind effects specified by ASCE 7-95, it did not enhance the information content of the provisions. In [2], a prototype of a DAD application called Frameloads was created and used to identify risk inconsistencies in the design of steel portal frames for low-rise buildings under wind loads. This prototype employed databases of aerodynamic pressure information to improve the load specification but did not possess many interactive capabilities and was not easily used in an iterative fashion, making it limited as a design tool. However, it served to identify features that are needed for the success of a DAD application. These include ease of use in an interactive, iterative design environment—simplicity of input, processing, and output is vital for practical design situations. Attention must be paid to the organization of the data within the databases to ensure that the data is easily integrated into the analysis. In addition, one must be able to move beyond the sample-dependent results associated with use of wind-tunnel (or, in the future, CFD) data and draw conclusions about the overall reliability of the design. Finally, the time needed to run the application should be reasonable; time-consuming analyses are not consistent with the need to iterate a design (see, e.g., [23]). The following section details how DAD application development issues are addressed in WiLDE providing a model for future DAD software.

We describe briefly the features of the aerodynamic databases. They consist, for a sufficiently large number of building geometries, of simultaneous time histories of pressures obtained at hundreds of taps on the exterior, and in some cases, the interior surfaces of the building. Protocols for the uniform archiving of data are currently being developed by the University of Western Ontario in collaboration with NIST, Texas Tech University, and Colorado State University. For the purpose of improving wind load descriptions, a "sufficiently large number" of building geometries means a number of geometries larger than the number of geometries on which the ASCE 7 Standard pressure charts are based. This latter number was about 20 for low-rise rectangular buildings [29]. It is anticipated that in the future much larger numbers of geometries will be represented in the aerodynamic database. In addition, interpolation procedure applicable to buildings with geometries for which no test data are available are being developed. It is also anticipated that the aerodynamic databases will be available to the public through a variety of distribution mechanisms. These may include electronic media such as CD-ROMs or DVDs packaged with the application software, or on-line access to files in public repositories maintained at an appropriate institution (e.g., a university or code-writing organization). For future research concerning aerodynamic databases, and observation, modeling, and scaling errors inherent in them, see Section 5.

3. Development and organization of WiLDE

3.1. Development

As mentioned in Section 2, WiLDE has its origins in a prototype application called Frameloads, used in [2] to study wind effects on moment resisting frames in low-rise buildings designed by the Standard Metal Building Manufacturers Association methodology (which is based on the ASCE 7-93 Standard). In its basic form, the software was designed to: (1) read information about the building geometry, frame properties, wind environment, and aerodynamic pressures databases, (2) compute the wind effect (bending moments, shears, and axial forces) time histories, and (3) print the results. Researchers subsequently attempted to expand Frameloads into a true DAD tool. Yang [30] presented the first working version (2.1) of the application WiLDE. This included graphical user interfaces (GUIs) that guided the user through the process of inputting structural design information, provided on-line help, and organized the program's output and post-processing options. The need for a more robust interface and better handling of pressure data files was addressed in subsequent versions [6]. Currently in version 2.7, greatly enhanced GUIs have been created that make entry of structural design information clearer and more easily controlled. The ability to directly accept input of influence coefficients that account for girt/purlin position as well as frame properties was added, expanding the applicability of WiLDE. Pressure data file manipulation is controlled within the program. For the output, an important post-processing option has been put in place—the ability to calculate realistic and robust statistical estimates of the peak load effect values based upon the entire time history, rather than upon the sample peak. While other improvements remain to be implemented, the current version of WiLDE has the ability to perform a wide variety of structural analyses that are not possible with current design technology. Some of these will be discussed below.

3.2. Organization

The program is organized into a series of windows, with one or more sub-programs or functions associated with each, as described below. Fig. 1 provides an overall flowchart of the program to clarify the scheme of the software. For software details, refer to [10].

3.2.1. Main driver

The main driver is used to control the processes of this program. Icons can be used for loading or editing data, performing the analysis, viewing the analysis results, clearing or saving the current input data, and getting help. Tool tips, pull-down

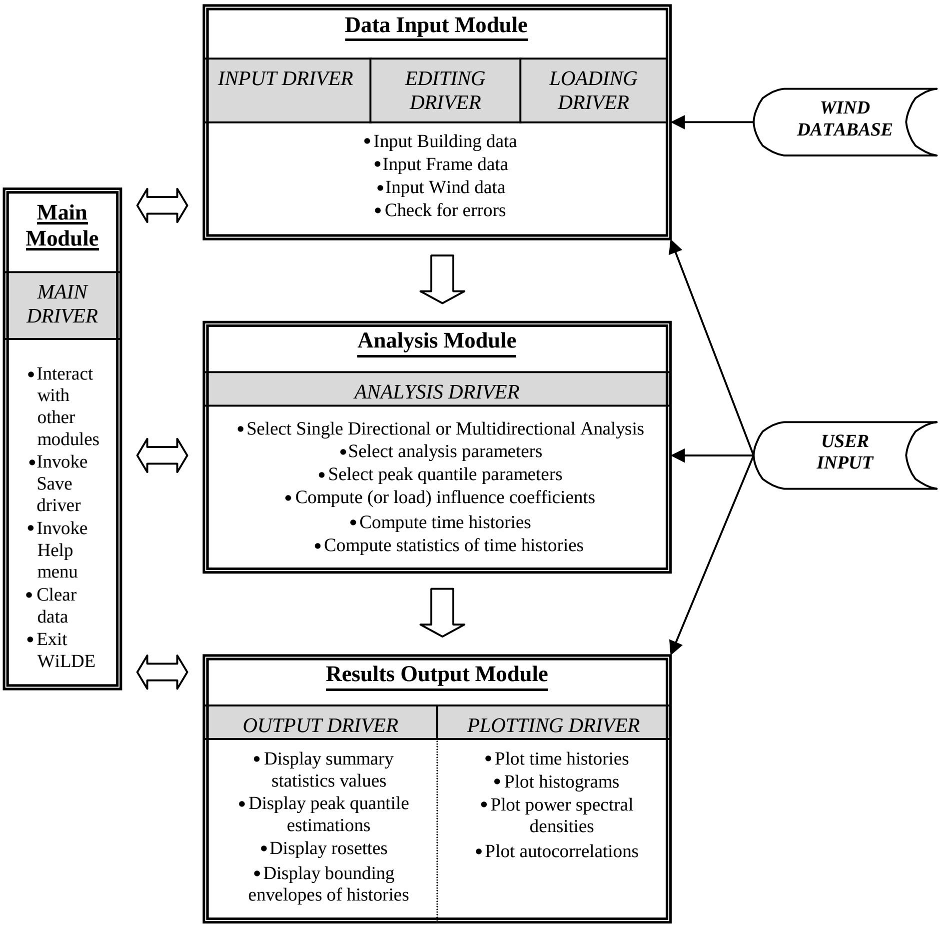

Fig. 1. Flowchart for WiLDE.

menus, and other features have been added to enhance the ease of use for the program as a whole—an important goal identified from previous versions of WiLDE.

3.2.2. Data input

Two mechanisms are available for data input: (1) the data may be loaded from pre-existing files, or (2) a series of GUI input windows may be utilized to enter the data interactively within the program. Note that there are different types of data needed by WiLDE, and each type may be entered by either mechanism. Fig. 2 shows an example of a typical input window in WiLDE.

Three major groups of input data are needed: building data, frame data and wind (environment and pressure) data. Each major group has different subgroups of

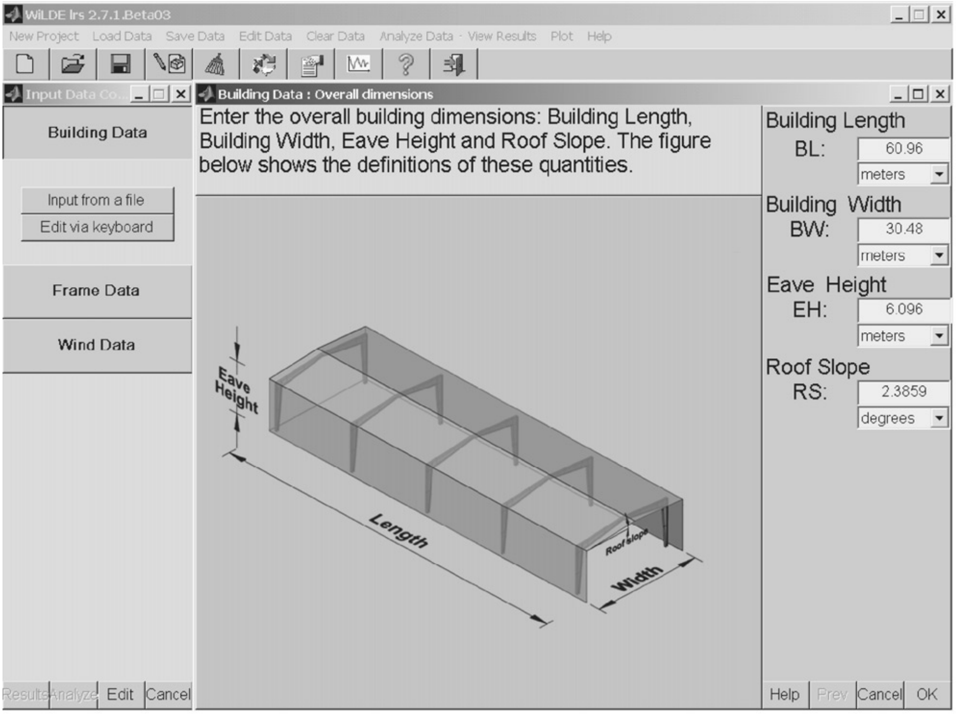

Fig. 2. View of a typical set of data input windows.

Table 1
Input subgroups for WiLDE

Input group	Input subgroups
Building data	Overall building dimensions
	Frame number and spacing
Frame data	Segment lengths for columns
	Cross-sectional properties for columns
	Segment lengths for rafters
	Cross-sectional properties for rafters
	Girt properties
	Purlin properties
	Critical sections
Wind data	Wind environment
	Wind-tunnel data

various input information listed in Table 1. Each subgroup has an associated GUI window to allow the user to input or edit the data through the keyboard. The GUI input windows are designed to guide the user through the input process while taking care of questions of format. The inputs are checked for certain errors (e.g., negative values, compatibility with other data, etc.), and error messages are displayed when appropriate.

3.2.3. Analysis

In this module, the computations of the wind-induced load effects at the selected frames and frame cross-sections are performed. Currently, the user may choose to analyze load effects (1) for wind speeds estimated regardless of their direction and blowing from any specified direction, or (2) for wind speeds specified as functions of direction, using the method described in [9].

The user may select the number of sampling points to be used in the analysis. This permits a "quick" analysis for exploratory purposes, or a "long," more accurate analysis. The user can specify up to three quantiles for which statistical estimations of the peak effect will be calculated. (Section 4.3 explains the importance of these estimations.) This part of the program is the most time-intensive, especially if a large time history of wind-induced responses is desired. The user is kept apprised of the progress of the program through this module through messages displayed in a separate window.

The load effect time histories are calculated using a quasi-static, linear elastic analysis that accounts for the geometry and cross-sectional properties of the statically indeterminate, identical frames, the position of the girts and purlins, and spacing of frames in the building. Each frame is responsible for resisting only those pressures exerted upon its tributary area; no load redistribution effects have been considered. WiLDE can accept direct input of frame influence coefficients via a file, permitting a wide variety of frame types to be considered in the analysis. When frame properties are input via the GUIs discussed in Section 3.2.2, however, it is assumed that the frame is symmetric, moment resisting, and has pinned supports at the ground.

3.2.4. Result output

In this portion of the application, the user can see displays of the results of the analysis portion of the program, sort the results according to various f ormats, display plots of time histories, and save some or all of the information. In the current version of WiLDE, two types of results are reported: summary statistics results and results on peak statistics. Fig. 3 illustrates an output window for WiLDE.

If the summary statistics results option is chosen, a brief synopsis of the load effect time histories is displayed. This synopsis includes the mean values, maximum values, minimum values, and standard deviations of the three load effects (bending moment, shear force, and axial force) at all selected cross-section locations on all selected frames. The results are shown in tabular form and can be organized in three formats—by frames, by cross-sections, or by load effects. Other post-processing options permit the user to plot the load effect time histories for a selected cross-section and frame or to save some or all of these results to a file.

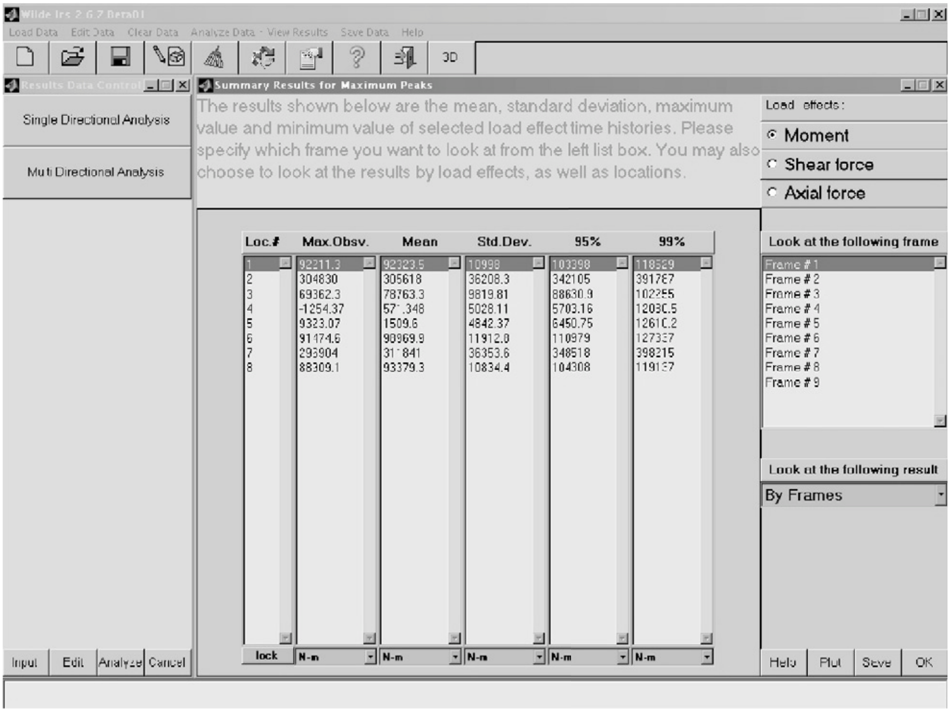

Fig. 3. View of a typical set of result output windows.

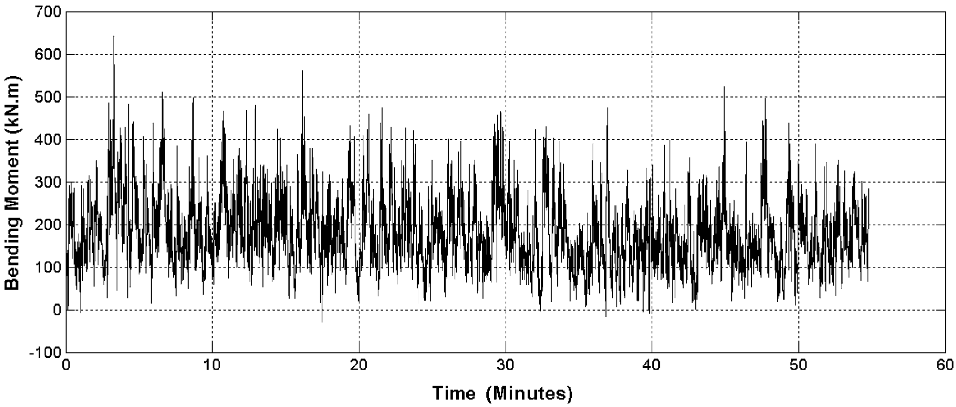

Fig. 4. A bending moment time history plot produced from WiLDE.

If the results on peaks statistics option is chosen, a table containing the results of a statistical analysis of the load effect time histories is displayed. (A typical output of a time history of bending moments at a specific cross-section in a frame under wind loading is shown in Fig. 4.) Estimates of peak load effect values (for both maximum and minimum values) having various probabilities of nonexceedance are presented, as well as their means and standard deviations. For comparison, sample observed peak values are also displayed. To estimate, from samples of duration T_1, the probability distribution of the largest peak in samples of duration T_2, WiLDE uses a procedure developed for processes with Gaussian marginal distribution [31] and subsequently extended to nonGaussian processes (see, e.g. [32]). (T_1 and T_2 are the prototype durations of the wind-tunnel pressure records and the assumed stationary portion of the storm affecting the structure, respectively.) See Section 4.3 for further discussion of the peak statistics analysis.

4. Illustrations of DAD capabilities

Tasks that have been performed effectively and in a realistic manner by DAD include:

(1) Analyses of wind direction effects, based on either (a) extreme wind speeds estimated without regard for wind directionality (in this case only the directional building aerodynamics is accounted for), or on (b) directional wind speed information (in this case both the directional extreme wind climate and the directional building aerodynamics are used). We refer to these two types of analysis as *nondirectional wind speed analysis* and *wind directionality analysis*, respectively.
(2) Estimates of ultimate capacities of frames under wind loading based upon local and global instabilities and plastic behavior.
(3) NonGaussian statistical analyses of peak load effects in low-rise buildings.
(4) Structural reliability estimates, with implications for reliability-based design and codification.

In this section, we comment in some detail on the above listed tasks.

4.1. Nondirectional analysis and wind directionality analysis

Nondirectional analyses are effected by assuming that the extreme wind speed rosette is circular; that is, the wind blows with the same speed from all directions. That speed is the result of statistical estimates that disregard the climatological dependence of the extreme wind speeds on direction. A simplified nondirectional analysis of bending moments induced in moment resisting frames of low-rise buildings was performed in [2], which found notable risk inconsistencies across locations within a frame and across different design choices. A more comprehensive study, using WiLDE, was performed by Yang [30], who documented dependences of all peak load effects on wind angle, frame location, and cross-section within the frame.

In contrast, a wind directionality analysis is performed using a noncircular extreme wind speed rosette. Codes such as the British Standard BS 6399 [33]

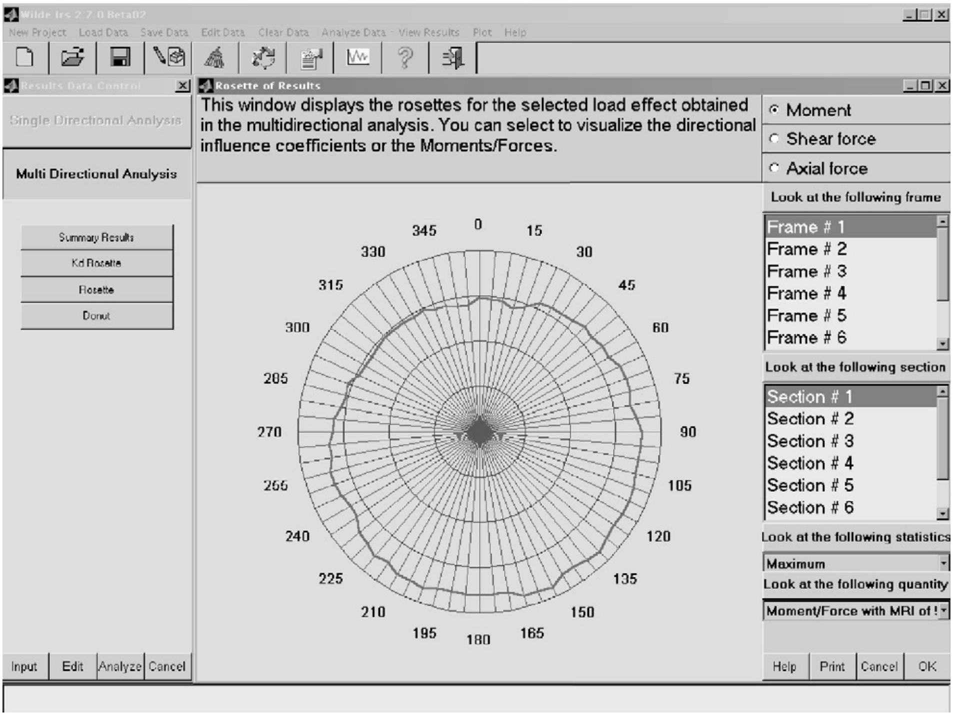

Fig. 5. Results for a directionality analysis in WiLDE of wind-induced bending moments.

and ASCE 7-98 do consider the effect of the dependence upon direction of both the building aerodynamics and the extreme wind climate. In ASCE 7-98 this is done for building design through a blanket directionality reduction factor $K_d = 0.85$ (see [34]) originally suggested by Davenport [35] by considering a hypothetical parent population overwhelmingly composed of very weak winds that are in fact irrelevant from an extreme analysis viewpoint. Using the DAD approach for hurricane wind speeds, Simiu and Heckert [36] and Rigato et al. [9] demonstrated that the effective directionality reduction factor for hurricane wind loads is a function of the mean recurrence interval of the wind effect. It may be assumed to be 0.85–0.90 for 50-year mean recurrence intervals, but is closer to unity for the large mean recurrence intervals associated with ultimate limit states—a fact not accounted for in current standards. See Fig. 5 for a typical rosette of bending moments at a specific cross-section in a frame for a mean recurrence interval of 50 years produced from WiLDE, showing the influence of directionality. For wind directionality analyses the climatological input used in WiLDE consists of simulated sets of hurricane wind speeds developed by Batts et al. [37]. These are the only sets of simulated hurricane wind speeds currently available in the public domain; other sets can be substituted if and when they are available.

4.2. Ultimate capacity under wind loading

The fluctuating pressures obtained from the aerodynamic databases are suitable for use in calculations of nonlinear frame behavior. In [3], estimated frame capacities were obtained from nonlinear finite-element analyses using ultimate states based upon local and global instabilities and plastic behavior. The DAD application WiLDE was used to determine the most unfavorable wind load for each cross-section of the frame, i.e., the load pattern acting on the frame at the time instant at which the peak wind effect is attained at a particular cross-section, e.g. the knee joint. The finite element analysis program ABAQUS [38] was used to perform ultimate strength analyses using the previously identified load distribution. The DAD capabilities of WiLDE permitted consideration of the effect of wind direction upon ultimate capacity.

The DAD approach revealed that ultimate capacities for frames designed by using ASCE 7 Standard wind loading are not risk-consistent—the capacities of their various cross-sections can vary widely. Table 2 (from [3]) shows factors λ corresponding to the loads that induce local buckling in frames with lower flange bracings at 2.5 m on center. Seven different design load cases are considered. The table shows the discrepancy between the ultimate capacities (as reflected by the magnitude of the factor λ) estimated using the ASCE wind loads (cases with W_S) versus those estimated using the more realistic aerodynamic pressures (cases with W_T). Since the capacity of the frame is controlled by the weakest cross-section, the material in the stronger cross-sections is wasted. The frame can be made safer by increasing the capacity of the weakest cross-section, and more economical by reducing the amount of superfluous material in the strongest cross-sections. These can be identified automatically by DAD. The joining of WiLDE and ABAQUS is an example of the power and versatility inherent in DAD.

4.3. Peak nonGaussian wind effects

Peak values in time histories of wind effects may be obtained: (1) as the largest observed peak in a 1 h time history, a method that may entail large errors due to the large variability of the peaks; (2) as the largest observed peak in a very long time history (e.g., 30 h), a method that is unduly conservative as well as being inconsistent with sound structural reliability practice; or (3) by using the entire information inherent in the time series of the wind effect, a method entailing the estimation of the probability distribution of the peak through the application of the classical Rice procedure [31] extended for nonGaussian time histories. DAD reveals that time histories of wind-induced load effects in low-rise buildings are typically nonGaussian (see, e.g. [39]). A procedure for calculating the peaks of nonGaussian processes based upon the translation process approach [32] is presented in [40]. This procedure was adapted for use in DAD by Sadek and Simiu [41], who investigated the choice and fitting to the data of the appropriate marginal distribution, and the effect upon estimation uncertainties of the duration and sampling frequency of the input aerodynamic time series. The results obtained by Sadek and Simiu indicated

Table 2
Ultimate strengths of frames for seven load cases, analyzed via the DAD approach

Load case 1 ($\lambda(D + L_R)$)	Load case 2 ($\lambda(D + W_S)$)	Load case 3 ($\lambda(D + W_T)$)	Load case 4 ($1.2D + \lambda W_S + 0.5L_R$)	Load case 5 ($1.2D + \lambda W_T + 0.5L_R$)	Load case 6 ($0.9D + \lambda W_S$)	Load case 7 ($0.9D + \lambda W_T$)
1.700	1.639	2.345	1.379	1.616	1.449	2.081

Note: D and L_R denote the ASCE 7-93 dead load and roof live load, respectively, W_S denotes the wind load calculated in accordance with the ASCE 7-93 Standard, and W_T denotes the wind load induced by pressures obtained in the wind tunnel.

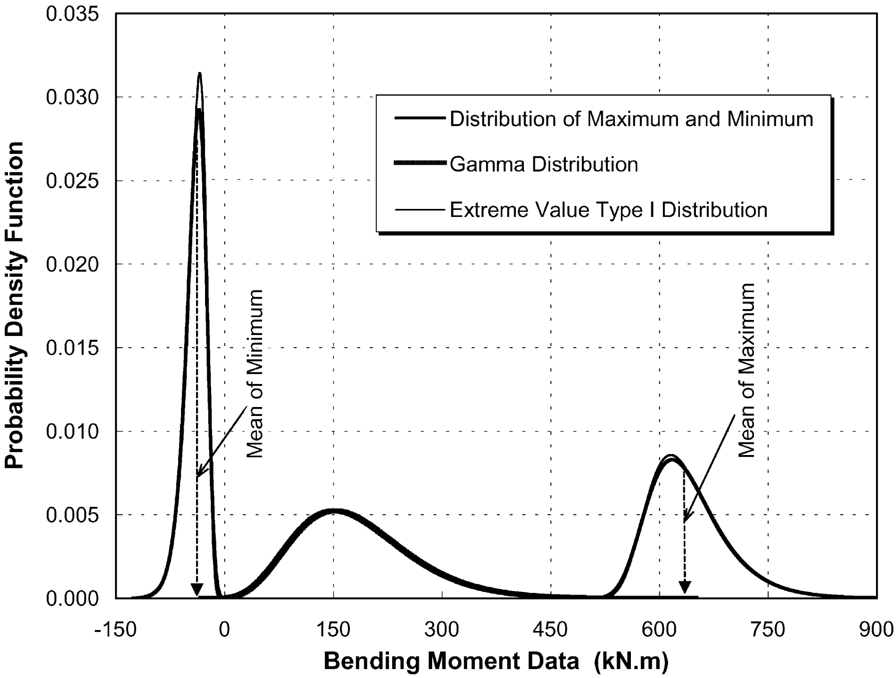

Fig. 6. Distribution of bending moments and the distributions of the maximum and minimum peaks for a typical time history.

that the gamma and the normal distributions are appropriate for estimating the peaks corresponding, respectively, to the longer and shorter tail of the time series' histogram. Using the translation process approach, it was found that the peaks distribution can be represented by the Extreme Value Type I (Gumbel) distribution. Fig. 6 shows the best-fitting gamma distribution and the distributions of the maximum and minimum peaks for a typical bending moment time history.

The output of the procedure consists of the mean of the peaks, their standard deviation, and a number of quantiles specified by the user for both the maximum and minimum peaks. Integration into a DAD environment such as WiLDE has the advantage of allowing the use in design and codification of robust estimates of statistics of peaks. This capability is useful in view of the significant variability of the peaks, and can be used effectively in a structural reliability context.

4.4. Structural reliability estimates

Structural reliability estimates were performed for buildings by Ellingwood et al. [34] using relatively crude approximations necessitated by the lesser computer capabilities available at the time. Current computational capabilities, as well as progress in the modeling of extreme wind speeds and relevant micrometeorological features, were used by Minciarelli et al. [42] to develop a DAD procedure allowing respectable estimates to be made of probability distributions of wind effects that incorporate uncertainties inherent in both the stochastic nature of the wind speed process as well as uncertainties inherent in insufficient knowledge. The latter include uncertainties with respect to the parameters of: the wind speed distribution (which in turn are due to the limited size of available climatological data samples); the terrain roughness characteristics; transformations of peak gust speeds recorded at weather stations and mean hourly speeds used in wind-tunnel simulations; relations between wind speeds in different roughness regimes; the features of individual wind tunnels; the relation between wind-tunnel and full-scale pressures; sampling errors in the estimation of peaks of the time histories of wind effects (for which a module is currently under development for incorporation into WiLDE); and so forth. Information on all these uncertainties is available or can be estimated by professional consensus.

An interactive module for performing reliability estimates can be easily integrated within the WiLDE-LRS software. Such a module would be a useful tool allowing standards committees to perform efficiently calculations that would provide a far superior basis for specifying load factors than the largely inadequate basis—which disregards even sampling errors in the estimation of wind speeds and uncertainties with respect to the actual terrain roughness—on which wind load factors are currently specified in the ASCE 7 Standard. The incorporation of this module in the WiLDE software is anticipated to be completed in the summer of 2002.

5. Conclusions and future research

The DAD approach for structures subjected to wind loads brings the wind loading side of the design process in line with the stress calculation side. It eliminates an anachronistic reliance on estimation methods designed for the slide rule and on "eyeball" development of code provisions from unrecorded pressure time histories used in conjunction with "hard-wired" structural information that may not be pertinent to the design at hand. DAD allows designs to be achieved that are both more economical and safer than designs based on conventional standard provisions.

A variety of important design capabilities can now be performed using applications that employ DAD. An example of such an application is WiLDE-LRS, which has been developed by the authors and their colleagues to explicitly incorporate DAD methods into an interactive, easy-to-use environment. Illustrations of novel design studies made using WiLDE have been presented in Section 4. Note that beta testing of the relevant software being developed at Purdue University and NIST is required, so that the resulting application satisfies the requirements of ease of use and usefulness in the field. Such testing is anticipated to take place in 2002.

Many new design capabilities beyond those discussed in Section 4 are now possible using the DAD approach. As an example, estimates of wind effects as a function of distance between frames can be obtained by using this approach. Most standard provisions assume that the design pressures acting on the frames do not depend on that distance. In contrast, DAD automatically accounts for the fact that, owing to imperfect across-wind correlation effects, the larger the distance between frames, the lower is the effective pressure acting on them.

While the focus of database-design research and development has so far been on frames of low-rise metal buildings, any other type of building or components can benefit from its use. This includes, in particular, girts, purlins, and other components of metal buildings, on which work is currently in progress at Lehigh University; and tall buildings, in which the dynamic effects can be estimated by DAD-type software in conjunction with conventional time-domain methods for the estimation of moments, shear, axial forces, displacements, and accelerations. The use of such methods has the advantage over dynamic wind-tunnel simulations of allowing the designer to study conveniently and comprehensively the effects of various structural designs upon the wind response, as well as the effects of various control strategies upon structural performance. Also, it is reasonable to anticipate that in not too distant future CFD calculations of pressure fields will become possible. The database-assisted approach can be used not only with wind-tunnel data, but with CFD-generated data as well, dramatically simplifying the design procedure for such structures. Finally, we mention potential applications to structures built of any materials, including reinforced concrete and wood, and to sets of buildings belonging to typical or individual developments, as opposed to buildings considered individually.

The utility of the DAD approach is limited only by the availability of validated techniques for generating, modifying, using, and verifying aerodynamic pressure data and the associated load effect results. Listed below are some research directions that will greatly enhance the role that DAD can play in solving future design problems.

- Pressures at eaves and corners of roofs can differ significantly in the wind tunnel from their full-scale counterparts. Routine methods are needed for correcting wind-tunnel pressure field datasets, so that the corrected data approximate better the actual full-scale pressures at corners and eaves.
- It was indicated in the paper that ultimate limit states can be estimated by considering the spatial variation of the tributary loads as obtained from the pressures measured in the wind tunnel, and that the spatial variation is currently based on one realization of the wind pressure field. A capability for the simulation of that process needs to be created that would allow several estimates of the tributary loads and their spatial variation. This would allow the estimation of statistics for the estimated ultimate limit states.
- For DAD to become routine, a sufficient number of data sets covering enough geometrical configurations and building dimensions are required. Methods of pressure field interpolation between buildings with relatively small differences in

geometrical structure are also necessary. Work toward developing such methods is currently conducted at Concordia University in Montreal. However, even if the number of geometrical configurations and building dimensions covered by pressure field data is only modestly larger than the number of such configurations and dimensions on which the ASCE 7 Standard is based, designs based on the approach described in this paper will be more realistic than current designs. In fact a comprehensive database can be developed in time, thus increasing significantly the advantages of DAD.

- As indicated in Section 3.1, better handling of the pressure database files has been a concern throughout the development of WiLDE. Currently, the University of Western Ontario is engaged in work to standardize the data format in which the pressure data are stored. Such an effort promises to improve the information content available for use by DAD programs such as WiLDE, as well as provide a stable platform for creation of new file access and manipulation tools. Integration of the proposed data format into WiLDE will be pursued in the next year at Purdue University.
- All of our DAD results were obtained by using UWO wind-tunnel pressure coefficient time histories under the assumption that those time histories were correctly measured. It is conceivable that wind-tunnel data obtained at other laboratories may differ to some extent from UWO data, or even that data measured at one laboratory at one time may differ from data measured at the same laboratory at another time. (Differences that may be expected between different realizations of a stochastic process are of course unavoidable.) In order to be able to use wind-tunnel aerodynamic databases confidently it is necessary to ascertain that wind-tunnel measurements meet minimum performance criteria. The development of protocols for quality control and certification of wind-tunnel measurements is therefore a necessary task. While it may not be expected that all wind-tunnel measurements would be equally accurate and precise, it is necessary to develop criteria defining acceptable deviations. Inter-laboratory test comparisons are a first step in this direction. Current efforts in these directions are in progress within the framework of the NIST/TTU program by UWO, Purdue University, and Colorado State University.
- In addition, owing to Reynolds number effects, wind-tunnel measurements of pressure coefficients may differ significantly from full-scale measurements at building corners and eaves. Much information is already available concerning such differences. It would be desirable to use that information to effect corrections, albeit approximate, to data obtained in the wind tunnel. This issue is currently being debated with representatives of various wind-tunnel laboratories.

Finally, we mention that an integration of information on probabilistic and knowledge uncertainty within a classical structural reliability framework is rendered easier and more effective by the use of DAD. The authors are currently engaged in the development of such a framework to be used for the improvement of current standard provisions and design practices for wind loads.

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