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Computational Wind Engineering Tools and Techniques

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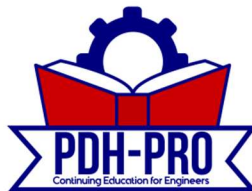
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1.0 Introduction

Computational Wind Engineering (CWE) is increasingly important for engineers who evaluate wind effects on buildings, structures, and the built environment. CWE uses computational methods, including computational fluid dynamics (CFD), to simulate wind flow, wind pressures, turbulence, and wind-related effects that have traditionally been studied using wind tunnel testing, empirical methods, and code-based procedures.

The purpose of this course is to introduce the current state of practice in CWE and explain the tools, methods, limitations, and research needs that are shaping its use in engineering design. The course is intended to help engineers understand where CWE can provide useful insight, where caution is required, and why verification, validation, and quality assurance are essential before computational simulations are relied upon for structural wind design.

This course focuses on two broad subject areas. The first is CWE methodologies, including existing tools and numerical approaches, their capabilities, and their limitations. This includes how computational tools are being applied to wind flow, building aerodynamics, environmental wind studies, and structural design questions. The second subject area is verification and validation of CWE methodologies. This includes the data, experimental methods, benchmark tests, and uncertainty evaluations needed to determine whether computational results are suitable for use in practice.

A central theme of this course is that CWE has significant potential, but it must be used carefully. Computational models can produce visually impressive results, but an attractive simulation does not automatically mean that the model is accurate, appropriate, or suitable for design. Engineers must understand the assumptions behind the model, the quality of the input data, the sensitivity of the results, and the level of uncertainty associated with the output.

1.1 Framework for Understanding CWE

To understand the role of CWE in engineering practice, it is useful to consider five areas that are essential to the overall analysis, design, and verification process. These areas interact and must be considered together when determining whether a computational wind study is appropriate for a particular project.

1.1.1 Computational Fluid Dynamics Design Tools

CFD-based design tools are central to CWE. These tools solve governing equations that describe fluid flow and use numerical methods to simulate wind interacting with buildings, terrain, and other objects in the built environment. In CWE, CFD tools may be used to study wind patterns around buildings, pedestrian-level wind comfort, pollutant transport, air quality, wind loads, and other wind-related design questions.

Current CFD tools include a range of numerical approaches. These may involve different turbulence models, particle-based simulations, high-resolution flow modeling, digital twin concepts, and machine-learning-based accelerators. Each approach has strengths and limitations. Some tools are better suited for rapid screening or qualitative understanding, while others may be



used for more detailed analysis when adequate modeling controls, input data, and validation are available.

One important area of development is the use of innovative technologies to make simulations faster and more practical. For example, machine learning and reduced-order modeling may help accelerate computationally demanding simulations. However, faster results are not useful unless they are reliable. Engineers must balance efficiency with accuracy and understand the limits of the selected tool before using the results in design.

1.1.2 Verification and Validation Benchmark Testing

Verification and validation, commonly referred to as V&V, are essential to the responsible use of CWE. These terms are sometimes used interchangeably, but they refer to different concepts. Verification addresses whether the computational model and numerical implementation are solving the equations correctly. In practical terms, verification is concerned with numerical errors, solution convergence, grid resolution, and other computational issues. Validation addresses whether the model adequately represents real wind behavior.

For CWE to become more widely accepted in structural design, engineers need reliable benchmark tests and clear expectations for uncertainty. Computational results should be compared with experimental results from wind tunnel laboratories and other accepted sources. Where applicable, the uncertainty associated with computational results should be evaluated against target uncertainty levels comparable to those obtained from physical testing conducted under recognized standards, such as ASCE 49.

V&V directly affects whether a computational result can be trusted. A model that has not been adequately verified may contain numerical errors. A model that has not been validated may produce results that do not represent real wind behavior. Both problems can lead to poor engineering decisions.

1.1.3 System Reliability and Risk

Computational modeling has become increasingly common in the built environment over the past two decades. It is now widely used for applications such as air quality assessments, pollutant entrainment studies, and pedestrian comfort evaluations. For some of these applications, simulations may be relatively short, and the computational mesh may be simplified. These approaches can be appropriate when the engineering question is limited and the desired output is not highly sensitive to complex turbulence or dynamic loading.

Structural wind design introduces a different level of risk. When simulations are used to estimate wind loads on structures, especially static and dynamic loads, the consequences of unreliable results can be significant. Simulations may have reduced reliability when results are needed in wake zones, when gust speeds are high, or when information beyond mean flow behavior is required. These conditions require more careful modeling, higher-quality input data, stronger quality assurance and quality control procedures.

One concern in CWE is the relatively low barrier to entry. Software availability can make it easy for users to generate simulations without fully understanding the limitations of the tools. This creates a risk that computational methods may be adopted too quickly for applications where standardized QA/QC protocols have not yet been developed. Engineers must consider when computational simulations are appropriate, when physical testing remains necessary, and when the reliability of the simulation outcome is acceptable.

1.1.4 Storm Type and Generation

Accurate wind loading depends on an accurate representation of the wind environment. For buildings and other structures, fluctuating wind pressures are especially important. These pressure fluctuations come from two primary sources: turbulence in the incoming wind field and turbulence generated as the wind interacts with the building itself.

To predict fluctuating pressures accurately, the computational model must include realistic boundary conditions for the incoming wind and sufficient grid resolution to capture important flow behavior around the structure. The model must also be capable of representing flow separation, wake formation, and other aerodynamic effects that influence pressures on the building envelope and structural system.

A major challenge in CWE is the specification of realistic turbulent inflow conditions. Engineers must consider both typical neutral surface-layer winds and extreme wind phenomena such as hurricanes, tornadoes, and downbursts. Each storm type can produce different wind characteristics, turbulence structures, and loading effects. Improving the realism of inflow conditions is one of the important opportunities for advancing CWE.

1.1.5 Structural Engineering Applications

CWE has become more accepted in the Architecture, Engineering and Construction industry for larger-scale flow modeling applications. However, using CWE to develop structural wind loads presents additional challenges. Buildings are bluff bodies, meaning that wind flow around them involves complex separation, reattachment, vortex shedding, and wake formation. These effects are difficult to model accurately and are important for both mean and dynamic wind response.

For structural engineers, key applications include the development of wind loads for main wind force resisting systems and the evaluation of wind-induced response, including lateral accelerations. These applications require careful attention to boundary-layer wind turbulence, local flow separation at the building envelope, wake behavior, and computational limitations. The engineer must also consider whether the model is suitable for the specific design question being asked.

Despite these challenges, CWE has significant potential as a structural engineering design tool. It may eventually provide engineers with greater flexibility to evaluate complex building shapes, site-specific wind environments, and design scenarios that are difficult to address using simplified methods alone. To reach this potential, continued collaboration is needed among researchers, practicing engineers, wind tunnel laboratories, software developers, and standards organizations.

2. Vision for the Use of Computational Wind Engineering

2.1. Current State of the Art

2.1.1. Computational Fluid Dynamics Design Tools

Computational Wind Engineering (CWE) involves the stochastic generation of wind velocities and loads, the utilization of database-enabled design tools, and the application of CFD to assess wind loading conditions and aid in the configuration design process of structures.

The CFD workflow encompasses setting up boundary conditions, selecting turbulence models, running solvers, and post-processing the results. In CFD, different numerical methods are used to solve the partial differential equations: finite difference method (FDM), finite element method (FEM), and finite volume method (FVM) (Ferziger et al., 2002). CFD software like OpenFOAM and Fluent commonly employ the finite volume method. The lattice Boltzmann method (LBM) (Chen and Doolen, 1998) offers an alternative approach known for its versatility and scalability. As for meshing tools, the immersed boundary (IB) method (Peskin, 2002) facilitates the simulation of fluid flow around complex geometries.

The Reynolds-averaged Navier-Stokes (RANS) approach is widely used in CFD as it requires modest computational resources, but its accuracy is compromised especially in separated flow regimes. Large eddy simulation (LES) provides higher fidelity by solving filtered Navier-Stokes equations but at a higher computational cost. Both low- and high-fidelity models can be utilized in different scenarios, depending on the need for rapid predictions or accurate assessments. Turbulence modeling is an important aspect of CFD, with various models available such as the k-epsilon and k-omega models in RANS. However, understanding the requirements and limitations of each model is important for accurate and reliable simulations.

In addition to these conventional numerical schemes, particle-based methods such as the LBM (Wikipedia, 2023a) and others based on smooth particle hydrodynamics (SPH) (Wikipedia, 2023b) are fast emerging for application to flow-structure interactions (Chang et al., 2022). Generating body-fitted meshes for flows around complex three-dimensional geometries is a time-consuming task. In addition, it requires considerable expertise in the use of mesh generation techniques. To address these shortcomings, immersed boundary methods have been developed for modeling flows around complex geometric shapes where surface geometry is not represented by body-fitted nodal points. This technology can be coupled with recent developments in image-processing techniques and three-dimensional scanning technologies to generate surface representations of complex objects. For example, scanned images of the surface topology of city blocks can be constructed from Google images that are already available in open domain. These images, which are in the form of stereolithography (STL) files, can then be immersed in the computational grid, and employing immersed boundary method, the pressure and velocity boundary conditions can be imposed on the immersed surfaces by employing the immersed boundary method.

Mostly, error bars are not included in the presentation of wind tunnel test results, which are essential to assess the reliability and variability of experimental measurements. Similarly, CFD predictions also lack explicit error bars. Therefore, including error bars both in wind tunnel and in CFD evaluations is essential to account for the uncertainties stemming from different sources.

Integrating machine learning (ML) techniques in CFD for wind applications has tremendous potential to accelerate the field while improving accuracy and computational efficiency. ML algorithms can optimize various aspects of the CFD workflow and optimize computational costs. Furthermore, ML can be applied to turbulence modeling, facilitating the development of data-driven turbulence models that effectively capture complex flow phenomena. This not only enhances the fidelity of CFD simulations but also reduces the computational effort required for accurate predictions. Additionally, the integration of hybrid neural solvers allows for efficient surrogate modeling, enabling the construction of accurate reduced-order models that approximate the behavior of complex simulations. By leveraging ML techniques and incorporating hybrid neural solvers, the field of CFD in wind applications can advance significantly, enabling faster and more accurate analyses.

2.1.2. Verification and Validation Benchmark Testing

Various definitions of verification and validation can be found in the literature; in some cases these are very similar, and in other cases they are contradictory, as also mentioned by Yeo (2020). Oberkampf and Trucano (2002) define the two terms as follows: Model verification is the substantiation that a computerized model represents a conceptual model within specified limits of accuracy, and model validation is the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. However, ASME (2006) states that verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution. Furthermore, in AIAA (1998) validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. During the workshop, the participants decided to define verification and validation as one (V&V).

Codes like the National Building Code of Canada (Canadian Commission on Building and Fire Codes, 2020) do not permit the use of CWE for design or give little information regarding the necessary V&V process (for example, ASCE 7, 2022), while waiting for more explicit provisions similar to ASCE 49 (2021), as also mentioned by Yeo (2020). In International Organization for Standardization document ISO 4354 (2020), CWE is referred to as a promising methodology that is evolving at fast pace, but it is still not ready to reproduce the fluctuating (dynamic) flow characteristics and pressure coefficients with confidence, thus it is not recommended for design wind actions. Architectural Institute of Japan document (AIJ, 2015) is the first consistent endeavor to propose a V&V process based on two steps (isolated building and building inside an urban area). A list of benchmark experimental results is available, but the V&V of LES and guidelines for how to implement meaningful numerical analysis have yet to be explicitly defined.

The vital part of the V&V of the CWE process refers to experimental results from wind tunnels. ASCE 49 (2021) was developed to ensure that wind tunnel tests are conducted so as to simulate the physical characteristics of wind. The provisions highlight the permitted assumptions and experimental techniques that can be used. Any wind tunnel test that respects these provisions has been demonstrated to lead to pressure results on building surfaces that structural engineers can trust for design purposes and that can thus be trusted for CFD V&V as well. A common theme in the literature is the inconsistency of experimental results among different wind tunnels and between wind tunnels and full-scale tests, both for local/overall and static/dynamic loads (Li et