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Overview of Quantification Methods for Wind Loads on Buildings

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Abstract— *Wind loads are one of the most important factors to consider while designing a structure. In previous research, multiple methods were used to test and measure wind loads – full scale measurement, wind-tunnel measurements, and analytical models and Computational Fluid Dynamics (CFD). In these methods, several researchers chose different types of parameters to quantify wind loads. While some of the parameters only focused on one or two aspects of wind loads, CFD simulation provides a more holistic measurement on responses of buildings to wind loads. Besides the quantitative measurement from CFD, its 3D visualization contouring capability could provide more detailed information on wind loads that can greatly assist building design and design optimization.*

Keywords— *3D visualizaiton countouring, computational fluid dynamics(CFD), presure coeficients, Strauhoul number, wind loads, wind tunnel.*

I. Introduction

Wind loads are one of the most important factors to consider while designing a structure. Sharp corners on buildings can produce wind flow separation, resulting in large wind-structure interaction induced stresses. Tall buildings especially are more susceptible to wind loads and wind induced excitations which have the potential to reduce their structural safety and cause discomfort to occupants. In addition, these excessive motions can create high base loads that increase the cost of the structure [1].

Research in the field of wind loads can be classified into two groups: modification in structure design to reduce stress from wind loads, and quantification methods of the wind loads. Previous research in first group was more concentrated on aerodynamics and sought to produce designs, configurations, or treatments that can improve structural integrity and mitigate wind loads when exposed to high winds [2].

This paper will focus on the second group – quantification methods of the wind loads. In previous research, wind loads were quantified through methods as following:

- Full scale measurements
- Wind-tunnel measurements
- Computational Fluid Dynamic (CFD)
- Database and analytical models

Researchers used different types of parameters to quantify the wind loads. All of these parameters will be reviewed and compared in this paper. This review can act as a guide regarding how to better quantify wind loads and develop holistic methods to evaluate wind loads on buildings.

II. Sources Of Data Collection

In the following, sources of data that previous studies used to quantify wind loads on buildings will be reviewed.

A. Full Scale Measurements

On-site full-scale measurements at real buildings provide the most representative data regarding wind loads on buildings. In these measurements, there is no needs to reproduce boundary conditions, no scaling issues, and no physical models to be adopted. However, full-scale measurements are complex and expensive, and are therefore mainly used for validation purposes [3]. As these tests would be conducted after building construction, this measurement cannot help at the design phase.

B. Wind-tunnel Measurements

Wind-tunnel experiments are generally considered the most reliable source of pressure data for buildings in the design phase [4]. Structural engineering uses custom wind-tunnel experiments to assess the wind loads on a specific building and considers geometry, immediate surroundings and appropriate approach-flow profiles of mean wind speed and turbulence.

Wind tunnel tests, like any scientific measurement, necessitate extra caution. A simple case of an isolated cube was tested in wind tunnels at 12 different institutions for 3 wind directions [5]. Test results varies less for the windward surface, while the roof and the leeward surface exhibit larger differences. Such differences could arise from errors in measurement equipment, physical variability of the flow due to different simulation methods, imperfections of the wind-tunnel, pressure tapping and tubing, imperfections of the software used for the data analysis, and human error [5].

Comparison between reduced scale structure experiments and on-site full-scale measurements was performed for an equivalent isolated cube case [6]. It shows the same differences before careful retesting. The history of calibration in the wind tunnel, quality assurance methods, and the know-how of the individuals participating in the test set-up and execution all have a direct impact on the quality of wind-tunnel results.

C. Computational Fluid Dynamics (CFD)

CFD has been used to study air flow around buildings for almost 50 years [7], while simulations focused on wind pressure on building facades emerged about 30 years ago [8-11]. At that time, computational simulation had many limitations [4]. With the advances in computational fluid

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dynamics and computing power of recent computers, CFD has significantly helped to chop aerodynamic design costs and time by reducing the amount of required structure tests, which uses a standard “trial and error” approach. The use of computational simulation to scan and screen many alternative designs has proved extremely valuable in practice.

The purpose of computational simulation methods should not merely be the analysis of prescribed shapes, but the automatic determination of the best shape for the intended application in order to ensure the realisation of the best design. This is the underlying motivation for the mixture of computational fluid dynamics with numerical optimization methods for aerodynamic shape optimization problems [2].

Thordal [12-14] conducted a series of research to improve accuracy of CFD when comparing it results to wind-tunnel measurements. With the latest improvements, modeling results have a greater agreement with wind-tunnel data during blind tests. The research also focused on standardizing CFD set up and data analysis. This will help to expand the application of CFD in quantifying wind loads on buildings.

D. *Database and Analytical Models*

When full scale tests, wind tunnel measurements, or CFD data are not available, getting data from other databases is another approach. The Air Infiltration and Ventilation Centre (AIVC) database [15,16] and the American Society of Heating and Air-Conditioning Engineers (ASHAE) Handbook are the most commonly referred to databases [17].

The analysis model consists of a set of equations used to calculate the pressure coefficient Cp for a specific building configuration [18,19]. They represent a user-friendly way to access large amounts of empirical data used in model formulas. The analytical model for Cp prediction is developed based on wind tunnels and full-scale experiments.

As part of the latest research, Muehleisen and Patrizib [20] analyzed the Tokyo wind pressure coefficient database and created a new set of spatially averaged wind pressure coefficients for low-rise buildings and developed a new predictive equation based on the new coefficients. The new parameter equation fits the Tokyo database value with goodness-of-fit R^2=0.992. Compared to the popular equation of Swami and Chandra, the new equation provides a better match to both the Tokyo and AIVC database coefficients, and is easier to calculate by hand or with a spreadsheet than the Swami and Chandra equations.

III. Type of Data Used To Quantify Wind Loads

Going through previous research, authors used different methods to collect different types of data to quantify wind loads. In the following, different type of data/parameters in past research will be reviewed. These reviews could provide guidance toward developing an all-inclusive approach that can combine elements such as geometry, wind speed, wind angle and pressure to quantify the wind load. This holistic measurement could better aid design engineers when looking for a standard for building structural integrity.

A. *Strouhal Number*

Strouhal number is a well-known critical parameter in regards to tall building designs [21]. When the wind blows over the blunt structure, the flow will separate and cause the vortex to fall off periodically. This periodic vortex shedding exerts transverse wind force on the building by generating fluctuating pressure. The Strouhal number is a non-dimensional parameter that defines the dominant frequency of the fluctuations in the across wind forces and is expressed as [2]:

$$S = f\,B/U \qquad (1)$$

where S is the Strouhal number, f is the frequency of vortex shedding, U is the wind speed, and B is the building width. The Strouhal number is a function of the shape of the building and has a value between 0.1 and 0.3. It is about 0.14 for a square cross section and 0.2 for a roughly circular cylinder [22].

Fig. 1. The Burj Khalifa building with a taper design and setbacks.

From expression of Strouhal number, it gives the frequency f at which vortices are shed from the side of the building, causing oscillatory across-wind forces at this frequency.

$$f = SB/U \qquad (2)$$

When the vortex shedding frequency f is close to one of the natural frequencies of the building, vortex-induced vibration will occur. This leads to an amplified across wind response. Vortex-induced vibration is the main problem of self-excited vibration of high-rise flexible buildings.

To reduce vortex-induced vibrations, taper and set-backs are used in tall building designs as shown in Figure 1. As building height increases, the building width B varies by decreasing. As a result, the vortices will try to shed at different frequencies at different heights. They become “confused” and incoherent, which can dramatically reduce the associated fluctuating forces [21].

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B. Pressure Coefficent

Pressure coefficients (Cp) is defined as follows [4]:

$$C_p = \frac{(P_x - P_0)}{P_d} \quad (3)$$

$$P_d = \frac{\rho U_h^2}{2} \quad (4)$$

where P_x is the static pressure at a given point on the building facade (Pa), P_0 is the static reference pressure (Pa), P_d is the dynamic pressure (Pa), ρ is the air density (kg/m3), and U_h is the wind speed, which is often taken at building height h in the upstream undisturbed flow (m/s).

Estimations of the wind pressure coefficients, Cp, on the facade of a building are required when using simplified and analytical wind load calculation procedures. Most wind load building codes [15, 23] suggest an approximate mean pressure coefficients for common building shapes. In addition to wind load calculations, wind pressure coefficients are also required in the estimation of air infiltration into buildings [24].

Three main methods commonly used to estimate Cp: full-scale building tests, wind tunnel tests, and parametric equations derived from experiments. Fully accurate determination of the Cp for a particular building can be obtained only from full-scale tests [25, 26] or wind tunnel tests [27, 28]. However, these kinds of tests are difficult, costly, and require significant time and expertise. For this reason, full-scale and wind tunnel tests are generally only used for the development of very complex high-rise buildings or wind pressure coefficient databases. The most common method for the prediction of Cp on low-rise buildings is the use of parametric equations derived from measurements which can provide reliable results if appropriately developed [27].

As one of the most popular databases of wind pressure coefficients, the AIVC database is a combination of different studies and presents Cp in tables as a single surface-averaged value for each face of the rectangular and square buildings for wind directions from 0° to 315° in 45° increments [4]. However, the database is very limited in terms of the number of side ratios and the rough increase in wind direction presented.

C. Holistic Measurement Through CFD

CFD provides a numerical method for simulating virtual wind tunnels to quickly and effectively evaluate pressure loads and dynamic wind loads. Figure 2 shows a sketch for a group of data that can be derived from CFD modeling. C_{fD} is along wind pressure coefficient, C_{fL} is across-wind pressure coefficient, C_{mT} is torsional moment, C_{MD} is mean along wind overturning moment cofficient, and C_{ML} is mean across-wind overturning moment cofficient. [29]

Furthermore, CFD can provide surface pressure distribution, mean surface pressures, minimum and maximum peak surface pressure coefficients and the floor-by-floor loadings [13].

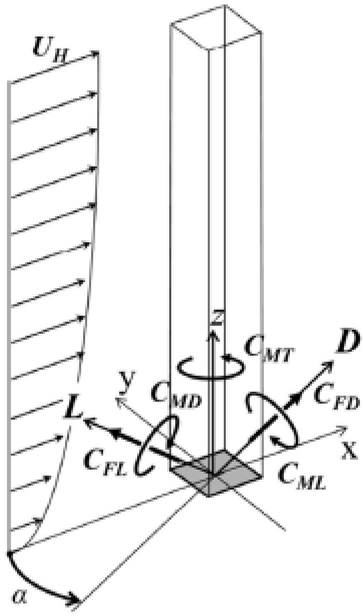
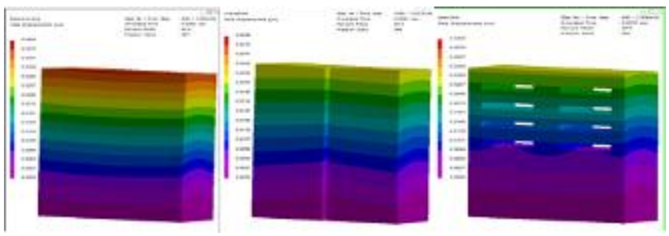


Fig. 2. Coordinate system and measurement data from CFD



(a) (b) (c)

Fig. 3. Distribution of stress on the building during wind load. (a) Baseline; (b) Middle split; (c) Top opening

As shown in Figure 3, to directly compare impact of wind load on a building, distribution of stress and deformation on the building under wind loads were simulated, analyzed and compared to optimize building design. Figure 4 shows comparison of stress-time profile from embedded stress sensors in the model of all designs [30].

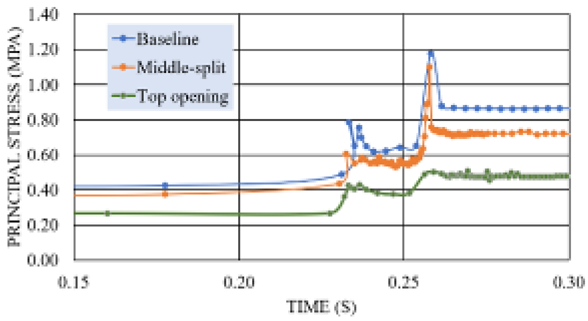


Fig. 4. Comparison of stress distribution on the building during simulation of wind-tunnel test

Accuracy of CFD results were validated with wind-tunnel experimental measurements. Figure 5 is a comparison between Large-Eddy Simulation (LES) results and wind-tunnel test data. CFD simulation results have good agreement with wind-tunnel experimental data [29].

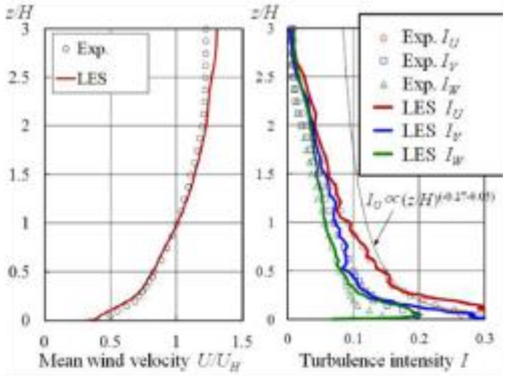


Fig. 5. Comparison between experimental and CFD results

Besides the quantitative data shown above, CFD simulation also provides 3D visual contouring for wind pressure, wind forces, wind speeds and others. The area where complex recirculation flow and vortex generating area can be identified and improved through design changes. These kinds of in-depth results are very important at the building design phase.

CFD results of the wind speeds around the tallest building in the world (Burj Khalifa) with a maximum peak speed of more than 60 miles per hour is shown in Figure 6. The freestream wind is invisible, and therefore the picture shows the accelerated (in red) and decelerated areas (in green and blue). Various strategies for optimizing skyscrapers, including tapering, softening of corners, and asymmetrical changes in cross-section, can effectively control wind.. These strategies prevent coherent wind effects and divide them into multiple different non-coherent parts of different frequencies and amplitudes along the building's height [31].

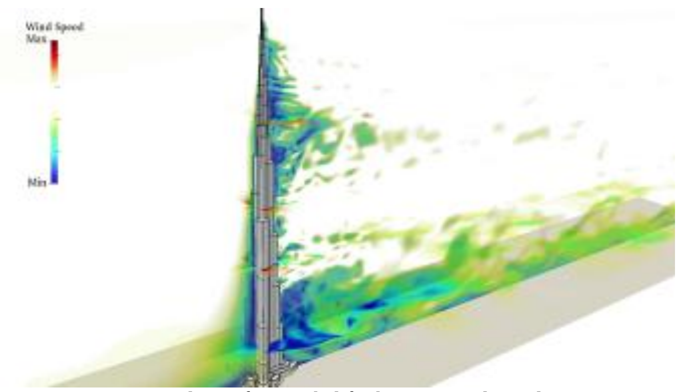


Fig. 6. CFD analysis of Burj Khalifa showing wind speed contours

As shown in Figure 7, close to the base, the cross-sectional area of the tri-branch and the wake behind the structure experience the largest wind effects, but the corner softening helps to avoid strong effects in different directions.

At intermediate heights, the cross-sectional area not only decreases but also changes between symmetrical and asymmetric shapes. A non-symmetric segment that suggests non-coherent vortex losing is highlighted. This helps to disperse the frequency of the crosswind throughout the height and avoid a single dominant oscillation.

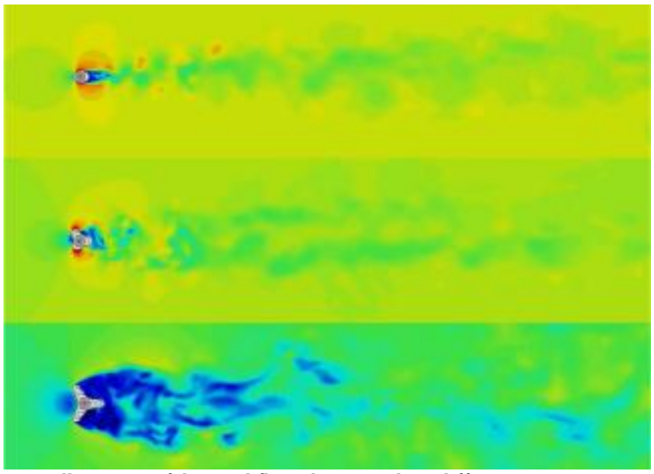


Fig. 7. Illustration of the wind flow physics at three different cross-sections of Burj Khalifa

The top of the building is experiencing the very best wind speeds, but because the cross-section area is quite small thanks to tapering, the wind forces are small also.

Comparing to other measurements of wind load, CFD can provide much wider range of evaluation of building responses wind load. With increased computational power and improved prediction accuracy, CFD simulation is becoming more and more widely used.

IV. Conclusion

Wind load testing methods and types of parameters used to quantify wind load were reviewed. Full scale measurement, wind-tunnel measures, analytical models and CFD are four main methods to collect wind load data. With increasing computational power and a deepening understanding of the physics of wind load, more and more research projects are using CFD to measure wind load on buildings.

Previous research used several different types of parameters to quantify the wind loads on buildings. All of them were reviewed in search for a holistic measurement of building response on wind load. Among them, CFD could provide data from different aspects to give holistic overviews on wind load on the buildings. In addition to quantitative measurement, CFD also provides 3D visualization of the full building with more detailed information that greatly assists building design and design optimization.

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