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Wind Analysis of Tall Building: A Review

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Abstract

Tall structures are particularly vulnerable to wind loads, due to their large surface area and height. Wind analysis of tall structures is therefore an important part of the design process, to ensure that they can withstand the expected wind loads. This review paper will discuss the different methods of wind analysis for tall structures, as well as the latest research in this area. The paper will begin with a brief overview of the different types of wind loads that can act on tall structures. This will be followed by a discussion of the different methods of wind analysis, including analytical methods, numerical methods, and physical modelling. The paper will then discuss the latest research in wind analysis of tall structures. This will include topics such as the development of new wind load models, the use of computational fluid dynamics (CFD) for wind analysis, and the development of new wind mitigation technologies. The paper will conclude with a summary of the key points and a discussion of the future of wind analysis for tall structures

Keyword: *CFD, Wind effect, Tall Building, ANN, Wind Tunnel Test*

1. Introduction

Impressive in their architectural grandeur, tall structures have become iconic symbols of contemporary urban landscapes. From the awe-inspiring Burj Khalifa in Dubai to the graceful Shanghai Tower in China, these monumental edifices continuously push the boundaries of engineering and design. Yet, as the pursuit of greater heights persists, a formidable adversary emerges: the relentless force of the wind. Wind, an elemental power, ceaselessly interacts with these colossal constructions, subjecting them to dynamic forces and potentially disruptive vibrations. As a result, comprehending and effectively addressing the impact of wind is of utmost importance for ensuring the safety, comfort, and optimal performance of these sky-scraping structures.

This review paper embarks on an extensive investigation into the pivotal domain of wind analysis concerning tall structures. It delves deep into the multifarious interplay between wind and tall buildings, encompassing aspects such as wind load computations, aerodynamic design, mitigation of wind-induced vibrations, and advanced analytical methodologies. Our objective is to untangle the complex web of obstacles and remedies within the realm of wind engineering as it pertains to tall structures. This endeavour draws upon the collective wisdom and expertise of professionals, scholars, and practitioners in this specialized field.The significance of wind analysis in the design of tall structures cannot be overstated. As the wind interacts with these buildings, it can generate intricate wind-induced forces, encompassing lateral forces and torsional effects, demanding precise prediction and mitigation. Furthermore, wind-induced vibrations can compromise the comfort and functionality of occupants, potentially leading to structural wear and safety hazards. Thus, it becomes imperative for engineers and architects to possess a comprehensive grasp of how wind interacts with tall structures, enabling the creation of designs that seamlessly blend aesthetics with structural integrity.

Throughout this review paper, we embark on a historical journey through the evolution of wind analysis, tracing it from its rudimentary origins to the cutting-edge technologies of the present day. Real-life case studies featuring iconic tall structures will serve as guiding lights, illuminating the profound influence of wind analysis on architectural decisions and structural innovations. Additionally, we will delve into advanced wind analysis methodologies, including the incorporation of artificial intelligence, machine learning, and big data analytics, all of which hold the promise of a transformative impact on the field.

The challenges and opportunities that lie ahead in the realm of wind analysis for tall structures will be a central focus of our discussion. We will explore forthcoming trends such as sustainable building design, adaptable facades, and the utilization of wind energy within these towering skyscrapers. By confronting these challenges and embracing emerging technologies, our objective is to underscore the enduring significance of wind analysis in shaping the future of tall structure design. Our review paper is constructed upon a solid foundation of peer-reviewed research, industry insights, and hands-on expertise. As we navigate this multifaceted terrain, we invite our readers to embark on a journey through the domain of wind engineering in tall structures. This journey offers both a retrospective look at past accomplishments and a visionary glimpse into the possibilities that lie ahead.

2. Literature Review

Tall buildings are inherently sensitive to the dynamic nature of wind. To illustrate this point, let's take a moment to consider the iconic Burj Khalifa, a symbol of human ambition and engineering excellence. Soaring to a remarkable height of 828 meters (2,717 feet), the Burj Khalifa serves as a striking example of how human ingenuity has conquered the formidable challenges posed by wind forces, encapsulating the core theme of this review paper. As observed by Fasoulakis and Laras (2010), "The design and construction of the Burj Khalifa stand as a testament to the remarkable advancements in wind engineering. Innovative solutions were employed to effectively manage the intricate interactions between wind and this towering architectural marvel.

A wealth of research exists concerning the wind analysis of tall buildings, with studies employing methods such as Wind Tunnel Tests, Computational Fluid Dynamics (CFD), and Artificial Neural Networks (ANN). However, the primary focus of this study revolves around optimizing wind response and refining building shapes, whether through minor adjustments or significant modifications. Through a series of in-depth case studies, we delve into how wind analysis has exerted a profound influence on the design and construction of iconic tall structures. Notable projects like the Burj Khalifa, Taipei 101, and the Shanghai Tower serve as exemplars, illustrating how wind analysis has played a pivotal role in shaping architectural decisions, fostering structural innovations, and enhancing safety protocols in the realm of tall building design. It's important to recognize that wind-induced vibrations can significantly impact the comfort, functionality, and safety of occupants within tall structures. In this section, we explore various strategies and cutting-edge technologies employed to mitigate these vibrations. These include the utilization of tuned mass dampers, tuned liquid dampers, and advanced materials. Real-world examples are presented to underscore the effectiveness of these solutions.

In Fig. 1, we can observe some of the world's top 10 tallest buildings. Over past decades, tall buildings typically adhered to traditional and symmetrical designs, featuring square, rectangular, triangular, or circular cross-sections. Examples of such designs include 432 Park Avenue in New York and the World Trade Center in New York. These traditional shapes were less prone to torsional vibrations induced by seismic loads due to their structural symmetry (Tanaka et al., 2012). However, the continuous progression of social and economic development, coupled with advancements in engineering and construction techniques, the availability of high-quality materials, including steel and advanced welded connections, and the use of lightweight facades (which do not contribute significantly to the structural strength), have inspired architects and engineers to pursue unique and slender designs for tall buildings.

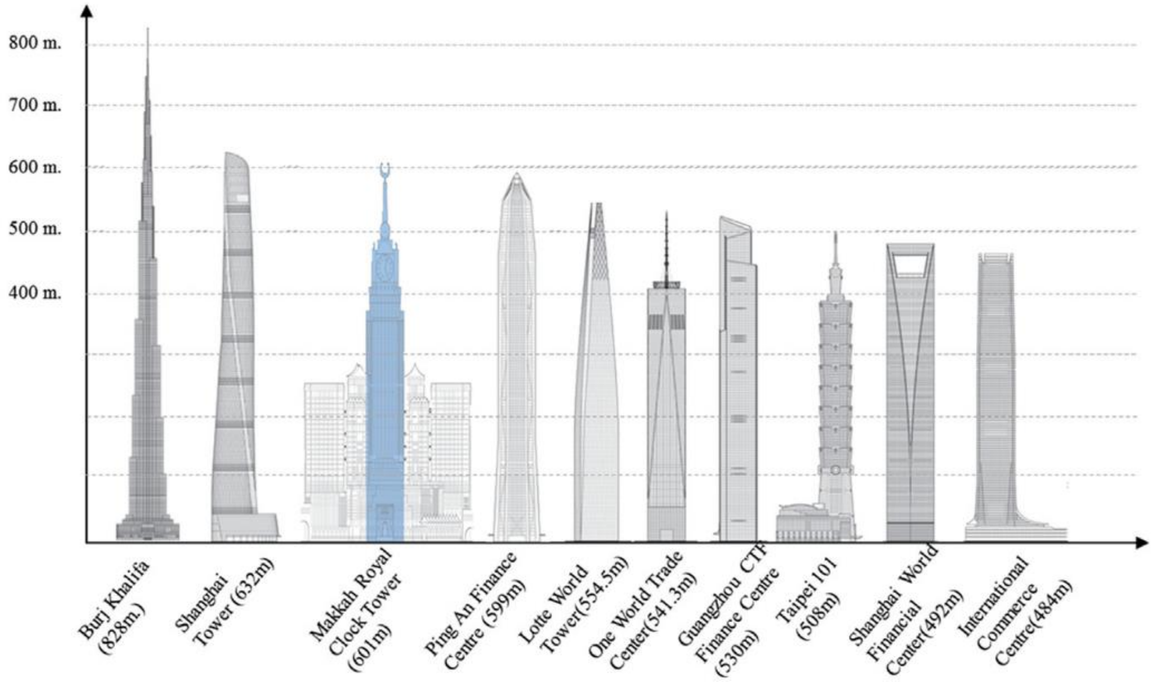


Fig. 1 Top tallest building in the World (Ashutosh et.al., (2018))

These innovative structures serve as showcases for their creativity, vision, and design concepts. Conversely, the pursuit of greater heights often results in increased flexibility, slenderness, limited damping, and lower natural frequencies (Kareem et al., 1999; Kim et al., 2008). As a structure's height increases, the concern over wind-induced dynamic responses becomes more pronounced, particularly in the context of wind gusts. Additionally, vortex shedding, a phenomenon where vortices periodically form and detach from the structure, assumes significance. These vortices can have frequencies close to the natural frequency of the structure, potentially causing vibrations that raise concerns about both serviceability and survivability (Xie 2014; Kareem 1983; Davenport A.G. 1971). It is widely acknowledged that the shape of a structure plays a pivotal role in its ability to withstand wind-induced loads and influences its response to wind forces in various directions.

Bluff structures are inherently more susceptible to excessive wind loads. Earlier research on this topic can be traced back to studies conducted by Lee (1990), Irwin (2008), and Nakamura (1993). Among various structural shapes, rectangular cross-section structures are found to be more susceptible to lateral responses compared to triangular, elliptical, and cylindrical shapes, which tend to offer greater structural efficiency. It's important to note that while wind load is influenced by the outer geometry of a building, it cannot be generalized for tall buildings due to the significant variability in shapes and the surrounding environment, making each case unique, as highlighted by Nakamura (1993). During the initial design phases, it is advisable to closely examine building design modifications as a means to alleviate wind loads and address concerns related to structural serviceability. In today's context, even when the structural safety of a building can be assured through the utilization of advanced structural systems and top-quality materials, the vibrations induced by wind gusts can extend beyond the comfort threshold for occupants. This can become a matter of concern, leading to issues such as fatigue in the building's lifespan, excessive noise, and the development of cracks (Elshar et al., 2017).

2.1 Study based on CFD

In recent decades, Computational Fluid Dynamics (CFD) has emerged as an invaluable technique for conducting wind-related research. Advancements in computational capabilities have significantly accelerated the progress of scientific work in this field. Originally driven by developments in the aerospace and automotive industries, CFD has now become a standard tool for a wide range of applications. These include assessing wind comfort in urban environments, studying building ventilation, and simulating fire safety scenarios. Due to the high level of credibility it has attained in these domains, numerous large engineering consultancy firms maintain dedicated CFD departments. These departments handle a wide spectrum of tasks related to fluid dynamics and wind engineering. Cochran and Derickson (2011) and Meroney and Derickson (2014) conducted comprehensive reviews of the various wind-related tasks that can be effectively addressed using CFD. Additionally, Cochran et al. (2015) engaged in discussions about which wind-related tasks should be considered to enhance building design. For stationary problems, Reynolds-averaged Navier-Stokes (RANS) simulations have been a staple for many years, providing valuable insights into the wind environment. These simulations are instrumental in improving pedestrian comfort in urban settings and have earned a status on par with wind tunnel testing in the field of engineering practice. Guidelines for using Computational Fluid Dynamics (CFD) for pedestrian comfort purposes are readily accessible. One such resource is the COST Action 732, as outlined by Franke et al. (2007). Additionally, there are CFD guidelines available for dispersion modeling, as discussed by Meroney et al. (2016). When dealing with non-stationary processes characterized by turbulence and flow separation, it becomes imperative to employ transient simulations, such as Large Eddy Simulation (LES). These simulations provide crucial information about peak values but demand a substantial computational capacity for accuracy. This requirement can lead to either extensive time consumption or the need for a very powerful computer system.

The mean wind velocity profile in the direction of the flow is typically characterized by either the Logarithmic Law or the Power Law. The specific shape of the velocity profile is contingent upon the roughness of the surface. The Logarithmic Law is inherently scale-dependent, as it is expressed in relation to the roughness length of the surface, denoted as "zo." This law is mathematically described as follows:

$$\overline{U}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z - z_h}{z_0}\right)$$

The Logarithmic Law incorporates several key parameters: κ, a constant known as von Karman's constant with a value of approximately 0.41; z_h, representing the zero-plane displacement; and u*, which denotes the friction velocity. The friction velocity, u*, depends on the shear stresses between the Earth's surface and the air, as well as the density of the air. On the other hand, the Power Law, used to depict the mean wind velocity profile, is scale-independent. It relies on the exponential parameter α and is expressed as follows:

$$\overline{U}(z) = \overline{U}_{ref} \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

where U_{ref} is the mean reference wind speed measured in the height z_{ref}.

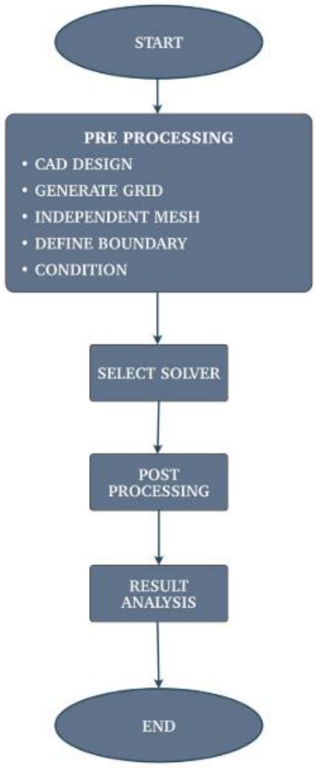
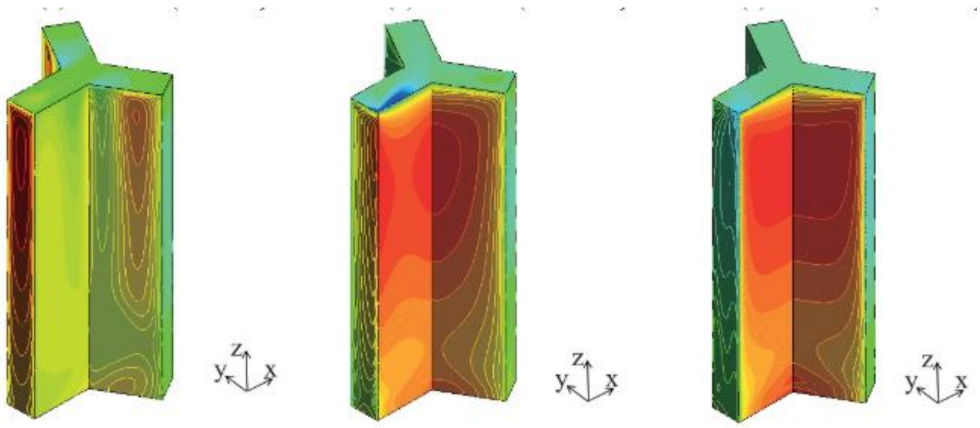


Fig. 2 Process flow of a CFD simulation

The hierarchy of resolved eddies within a turbulent flow is contingent upon two critical factors: the turbulence model chosen and the resolution of the computational mesh. In Fig. 1, we can observe the correlation between the Power Density Spectrum (PDS) of wavelength distributions in a turbulent flow and the various turbulence models employed. Notably, the Kolmogorov 5/3 power law is highlighted within the figure. This law holds immense significance as it delineates the inertial subrange, where flow behaviour becomes independent of viscosity, and substantial dissipation is minimal.

In a study conducted by Dagnew and Bitsuamlak (2014), three different inlet boundary condition techniques were compared. These techniques included the original Random Flow Generation (RFG) method as proposed by Smirnov et al. (2001), the Detached-eddy Simulation Random Flow Generation (DSRFG) method introduced by Huang et al. (2010), and the Recycling Method as outlined by Lund et al. (1998).



a) Pressure contour

b) Stream line

Fig.3 Post processing results (Sanyal and Dalui (2020))

The study involved a comparison between the numerically generated Power Density Spectrum (PDS) and the von Karman spectrum in the direction of wind flow. As anticipated, notable differences in the PDS were observed for the original RFG method, primarily because it does not conform to the von Karman spectrum. Conversely, the Recycling Method was found to produce an excessive number of high-frequency eddies, resulting in a wind flow that deviates from realistic expectations. The Detached-eddy Simulation Random Flow Generation (DSRFG) method, as developed by Huang et al. (2010), exhibited only a minor discrepancy in high-frequency components. Nevertheless, the study's conclusion was that this inflow method met the necessary criteria for simulating turbulent flows. Therefore, it can be effectively utilized in scenarios where factors like flow separation and pressure gradients cannot be disregarded, such as in the analysis of fluid flow around ships, as highlighted in Zhang et al. (2006).

The RMS model plays a significant role by predicting pressure strain in all regions and units, allowing for comparisons across various flow properties. partially resolves pressure strain, as highlighted by John et al. (2020). It operates similarly to RANS (Reynolds-Averaged Navier-Stokes) modeling and LES (Large Eddy Simulation) turbulence models, which are commonly employed for flow predictions. In the case of LES, it filters out small turbulence eddies to reduce computational demands, as it's observed that larger eddies contain a majority of the energy, as noted by John et al. (2020). To obtain more reliable results while minimizing computational costs, Large Eddy Simulation (LES) is often preferred, as discussed by Jameson and Witherden (2017). In an experimental setup designed to examine the spray pattern, the K-epsilon turbulence model is commonly used. This model is particularly advantageous because it is fully integrated with a Lagrangian particle tracking model, making it capable of accounting for droplet trajectories, as highlighted by Baetens et al. (2007). In aerospace applications, the Spalart-Allmaras turbulence model, as discussed by PrabhakaraRao and Sampath (2014), is frequently employed. This model is a one-equation model known for its ability to handle near-wall boundary flows effectively. It yields reliable results, particularly in cases involving adverse pressure gradients in the boundary layer. The general steps involved in a typical Computational Fluid Dynamics (CFD) analysis are illustrated in Fig. 2. With the ever-growing volume of data production, Machine Learning (ML) techniques are gaining prominence, as noted by Pandey et al. (2014). In the post-processing stage of the analysis, various results are generated, including pressure contours, streamlines, and velocity contours. These post-processing results are depicted in Fig. 3.

2.2 Study based on ANN

Vyavahare et al. (2012) conducted a study emphasizing that tall buildings possess a natural characteristic of being slender and flexible structures. It is essential to thoroughly investigate the impact of wind-induced excitations along and across the path of wind in specific regions. The Indian code of practice for assessing wind loads on buildings and structures, specifically IS-875 Part-3 1987, provides a procedure for determining the response of tall structures to wind loads along the wind direction. However, it does not currently address the across-wind response and interference effects. To address this gap, an article titled 'Review of Indian Wind Code IS 875 (Part 3) 1987' was prepared by IIT Kanpur under the GSDMA project. This article offers recommendations for determining the across-wind response of tall buildings and structures, following the guidelines outlined in the Australian/New Zealand standard 'Structural Design Actions – Part 2 Wind Action (AS/NZS 1170-2: 2002). In the Australian structural design code, obtaining the cross-wind response necessitates the computation of the coefficient (Cfs). This code provides specific figures and expressions for selected (h:b:d) ratios to determine C_{fs}. Neural networks were employed in a study by Verma et al. (2014) to estimate mean external surface pressure coefficients for tall buildings. They also proposed a simplified approach for estimating the dynamic along-wind response of tall buildings, based on the Indian Wind Code, as discussed by Nikose and Sonparote (2018). Furthermore, in the pursuit of developing proper orthogonal decomposition-based reduced-order models for quasi-static geophysical turbulent flows, Son et al. (2018) utilized artificial neural networks (ANN). This approach aims to provide an efficient and cost-effective computational tool for estimating the wind response of buildings, a concept also explored by Nikose and Sonparote (2018).

3. Future Trends and Challenges

As we peer into the future, the domain of wind analysis for tall structures presents an array of fresh challenges and exciting opportunities. In this section, we delve into forthcoming trends that are poised to reshape the landscape of tall structure design. These trends encompass sustainability considerations, the advent of adaptive facades, and the seamless integration of renewable energy generation within these towering edifices. However, it is essential to acknowledge the potential hurdles and complexities associated with implementing these progressive trends.

4. Conclusion

In closing, this review paper accentuates the critical significance of wind analysis in shaping the design, safety, and operational efficiency of tall structures. It offers insights into the historical evolution, contemporary methodologies, and prospective directions within the field of wind engineering. By promoting ongoing research and innovation, we emphasize the enduring relevance of wind analysis in navigating the ever-evolving landscape of architectural endeavours.

- Wind analysis is a crucial component of the design process for tall structures, ensuring their ability to withstand anticipated wind loads.
- Various methods exist for wind analysis, each with distinct pros and cons.
- Ongoing research in this field aims to enhance and develop new wind analysis techniques while also deepening our comprehension of intricate wind-structure interactions within tall buildings.
- This research is driving the creation of more precise and dependable wind analysis methods, ultimately bolstering the safety and resilience of tall structures.

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