

Wind effects on Buildings and their environment: codification and standardisation

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ABSTRACT

There is a growing interest in wind-induced structural effects within the field of wind engineering. The paper explores recent breakthroughs and advancements made in the wind engineering design over the past four decades. The various approaches employed in wind engineering, including wind tunnel testing, computational fluid dynamics (CFD) and field measurements, are highlighted. Furthermore, the paper critically examines the evolution of wind codes and standards, particularly focusing on their application to low-rise buildings and their attachments, while also addressing emerging research areas such as non-synoptic wind effects on buildings, wind loads and effects on building-attached/integrated photovoltaics (BAPVs/BIPVs), the advancement of numerical methods in structural wind engineering and the possible implementation of performance-based wind engineering. The paper provides valuable insights into the future directions of wind engineering, with a particular focus on contributions to the development of wind codes and standards at both national and international levels.

KEYWORDS Wind engineering; wind codes and standards; CFD; wind tunnel; low-rise buildings; attachments

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1. Introduction

Wind engineering encompasses several branches that address different aspects of wind effects on structures and the environment, namely structural wind engineering, environmental wind engineering and wind energy engineering. Structural wind engineering focuses on the wind interaction with structures and aims to ensure their safety and structural integrity. It involves assessing wind pressures, aerodynamic forces and vibrations on buildings, bridges and other infrastructure. Environmental wind engineering investigates the impact of wind on the natural and built environment. It includes examining wind flow patterns around buildings and urban areas, assessing pedestrian comfort and evaluating the dispersion of pollutants. Wind energy engineering is dedicated to the utilisation of wind as a renewable energy source, involving the design, optimisation and operation of wind turbines at different settings to maximise energy generation and efficiency. It is important to recognise that these branches are interconnected, as knowledge and insights gained from one branch often inform and influence the others. For example, understanding wind flow patterns and turbulence in environmental wind engineering can provide valuable inputs for optimising the structural design of buildings.

Three primary methodologies used in wind engineering are Atmospheric Boundary Layer Wind Tunnel (ABLWT) Experiments, Computational Simulations and Field measurements. While the diversity of the available methodologies is an advantageous factor that aids in overcoming the limitations inherent in each method individually, ABLWT testing is considered the most

dependable approach in wind engineering followed by Computational Simulations. Field measurements are always crucial for verifying the accuracy of both experimental (wind tunnel) and computational (CFD) results.

The contribution to the development of wind design standards is crucial for various reasons. Primarily, it facilitates the integration of academic research with industry practices, enabling the application of the latest scientific discoveries and methodologies in practical and real-world issues. Moreover, it ensures that constructions stay current with the latest advancements and improves their resilience and sustainability.

In examining the evolution of wind codes and standards, it is pivotal to consider the role of international standards such as ISO 4354, titled “Wind Actions on Structures”. Established by the International Organization for Standardization (ISO), this standard provides a framework for assessing wind loads on structures. This standard was originally developed by ISO/TC 98/SC 3 in 1997 and it has undergone several revisions to integrate the latest advancements in wind engineering. The current edition replaces the first edition (ISO 4354, 1997) with significant technical revisions aimed at enhancing the reliability, simplicity and relevance of the standard for engineers, architects and regulatory bodies globally. Through systematic updates meticulously crafted by ISO/TC 98/SC 3/WG 2 working group, ISO 4354 aims to remain a globally applicable resource, aligning closely with contemporary wind codes and facilitating the adoption of recent research outcomes in this field.

2. Contributions in wind engineering

This section is dedicated to reviewing some remarkable contributions in the field of wind engineering made by the Building Aerodynamics research group at Concordia University in Montreal, Canada, under the leadership of the first author over the past 40 years. The Boundary Layer Wind Tunnel, established in the early 1980s within the Department of Building, Civil and Environmental Engineering (Stathopoulos, 1984), has been instrumental in these efforts. Since then, the research group has carried out extensive studies on wind effects on buildings and their environment making significant contributions to the development of wind codes and standards of practice in the field.

The extensive research conducted in the mid-1970s, which involved atmospheric wind tunnel tests on various low-rise building geometries (Davenport et al., 1977, 1978), played a critical role in establishing guidelines and provisions for assessing the wind pressures on these structures. Additionally, the research conducted by Surry and Stathopoulos (1978) on assessing instantaneous area-averaged pressure coefficients through the pneumatic-averaging technique significantly enhanced the understanding and quantification of wind pressure distribution on building surfaces. These studies formed the basis for developing provisions in wind codes and standards for evaluating wind loads on low-rise buildings.

Drawing upon the foundational conceptual model for wind-induced loads on and response by buildings, reference is made to the Wind Loading Chain, developed by Alan G. Davenport, as illustrated in Figure 1.

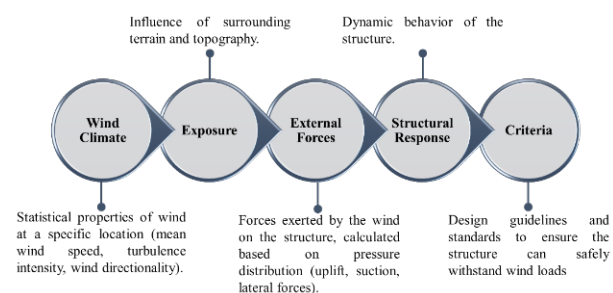


Figure 1. The Wind Loading Chain by Alan G. Davenport (after Davenport, 2002).

This wind loading chain concept effectively demonstrates the intricate interaction between the atmospheric boundary layer and structures, highlighting the importance of comprehending and assessing each component of the chain to accurately evaluate the wind effects on buildings and related structures. In this paper, the Alan G. Davenport Wind Loading Chain serves as a conceptual framework to structure and guide the presentation of the research findings.

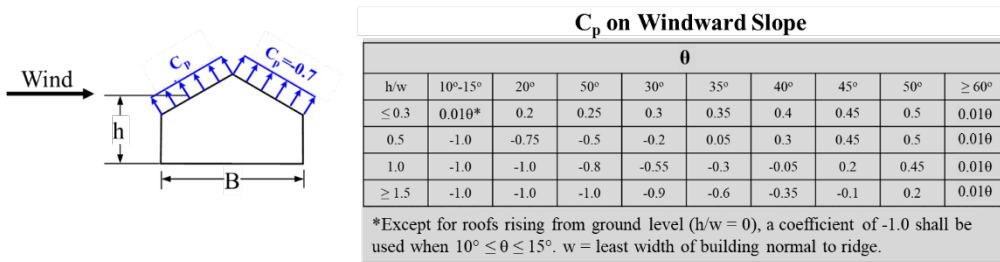
2.1. Components and cladding (CC) wind pressures

The determination of design external pressure coefficients for low-rise buildings is mainly influenced by factors such as geometric dimensions, building shape and wind characteristics. Canada's provisions for wind loads on these structures have received widespread recognition and praise internationally. Researchers and professionals worldwide have acknowledged the innovative and pioneering nature of these provisions, which have had a significant impact on the development and advancement of wind load standards at both national and international levels, including standards such as ASCE/SEI 7, the ISO 4354 and the China Standard for Wind Loads on Roof Structures.

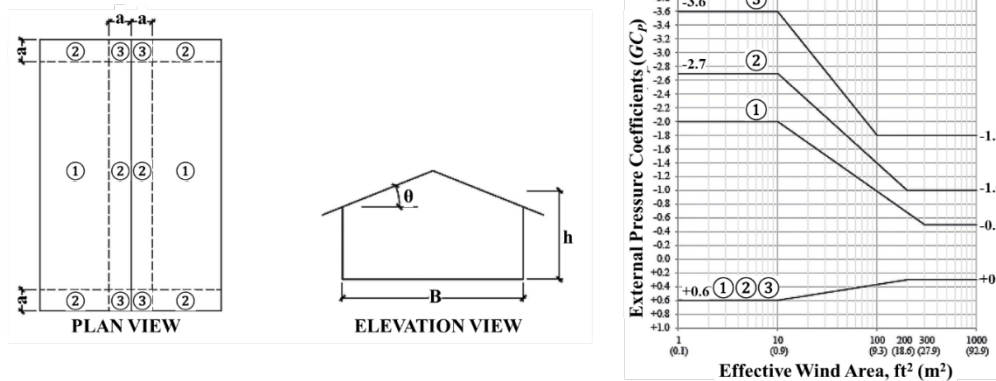
As a result of extensive studies focused on the influence of roof shape, slope and geometry for low- and medium-rise buildings, current international wind codes and standards cover a broad spectrum of geometries and configurations. These studies, including Stathopoulos and Dumitrescu-Brulotte (1989), Stathopoulos et al. (1990), Doudak et al. (2009), Alrawashdeh and Stathopoulos (2015) and Aldoum and Stathopoulos (2020) for flat roofs; Stathopoulos and Saathoff (1994), Stathopoulos et al. (2001) and Chavez et al. (2022) for gable roofs; Stathopoulos and Mohammadian (1986, 1991), Saathoff and Stathopoulos (1992) and Stathopoulos and Saathoff (1992) for monoslope and sawtooth roofs; Shao et al. (2018, 2019) for L- and T-shaped buildings of complex roofs; and Stathopoulos and Luchian (1990b, 1990) and Aldoum et al. (2023) for stepped roofs, have contributed to the comprehensive understanding of wind-induced loads on various roof types. These findings have significantly influenced the development and refinement of international wind codes and standards, particularly the gust pressure coefficients of ASCE/SEI 7 (USA), NBCC (Canada) and GB 50009 (China).

To demonstrate the evolution of pressure coefficients of components and cladding in the American standard over time, Figure 2 depicts the design pressure coefficients for gable roofs as specified in ANSI A58.1 (1972) and ASCE/SEI 7 (2022). The incorporation of area-averaged pressure coefficients, which relate pressure coefficients to the effective wind area of a façade, reflects a more nuanced understanding of wind dynamics (Surry and Stathopoulos, 1978). This approach recognises that wind pressures on building surfaces are not uniform but vary significantly across different areas of the building envelope.

(a)



(b)



Notes

1. Vertical scale denotes (GC_p) to be used with q_p .
2. Horizontal scale denotes effective wind area A, ft² (m²).
3. Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
4. Each component shall be designed for maximum positive and negative pressures.
5. Values of (GC_p) for roof overhangs to be determined in accordance with Section 30.7 Roof Overhangs.

Figure 2. Design pressure coefficients for gable roofs specified by: (a) ANSI A58.1 (1972); and (b) ASCE/SEI 7 (2022).

2.2. Primary structural system forces

The early work by Davenport et al. (1977, 1978) focused on evaluating various structural actions for rectangular buildings, including total uplift, total horizontal shear, bending moment at knees and bending moment at the ridge. This evaluation was based on the concept of time averaging and spatial averaging of the peak measured pressures. Building on this basis, Figure 3 further elucidates the fluctuating nature of wind loads on low-rise buildings, showcasing localised wind effects and time-varying responses such as bending moments and uplift forces.

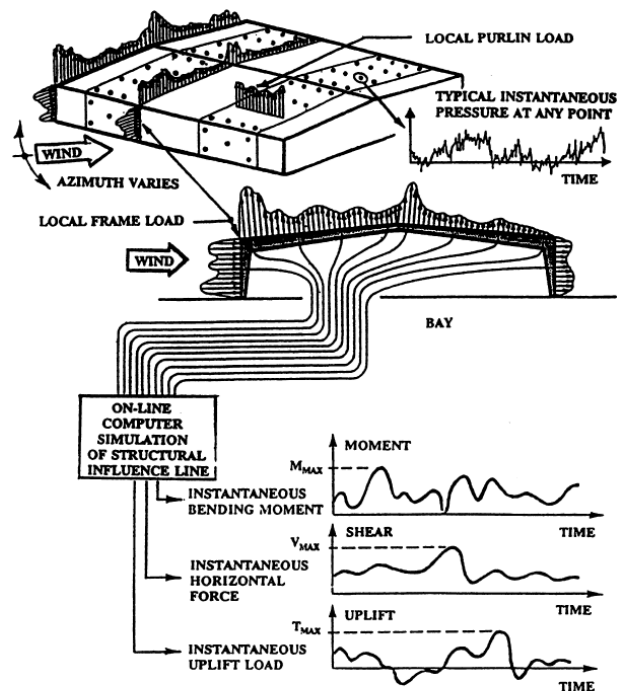


FIGURE C6-6 UNSTEADY WIND LOADS ON LOW BUILDINGS FOR GIVEN WIND DIRECTION (AFTER REFERENCE [C6-68])

Figure 3. Fluctuation of wind loads on low buildings for a specific wind direction (ASCE/SEI 7, 2022).

To deepen the understanding of how wind loads are transferred through the components of a building and to assess the 0.8 reduction factor introduced by Alan Davenport, which accounts for various alleviating considerations like terrain roughness and wind direction, a thorough study was conducted by Zisis et al. (2011). This study involved field measurements, wind tunnel tests and Finite Element Method (FEM) analysis. The focus was on a single-storey residential building with a rectangular layout measuring 8.6 x 17.2 x 5.6 m, featuring a duo-pitch roof with a slope of 4/12 located on the campus of the University of New Brunswick (UNB). The wind tunnel tests were conducted at a scale of 1:200, simulating a relatively open-suburban terrain in the atmospheric boundary layer wind tunnel of Concordia University. The study revealed that there is a wind load reduction ranging from a minimum of 17% to a maximum of 28% at the foundation level, depending on the wind direction. These findings have significant implications for the structural design of low-rise buildings and partially explain the rationale for the 30% reduction in the effective wind load applied to the foundation recommended by the National Building Code of Canada (NBCC, 2020).

In response to the needs of wind codes and standards in this context, a series of studies have been conducted to investigate wind-induced shear force and torsion on different types of low-rise buildings. These studies, conducted by Stathopoulos et al. (2013) and Zhang et al. (2014), examined rectangular flat- and gable-roofed buildings as well as L-shaped low-rise buildings. The investigations encompassed various configurations, including different terrain exposures, wind directions and building heights. The findings of these studies revealed that the torsion on low-rise buildings is significantly influenced by building geometry, wind direction and terrain exposure. Notably, the torsion coefficients on L-shaped buildings were found to be much higher compared to rectangular buildings. The findings of the study warrant the introduction of provisions for wind-induced torsion in wind loading standards and building codes.

2.3. Elements attached to the building envelopes

Numerous experimental and field investigations have been carried out to examine wind loads on building elements, such as parapets, canopies and solar panels. In early studies, Stathopoulos and Baskaran (1987) and Baskaran and Stathopoulos (1988) investigated the impact of parapets on roof wind loads using atmospheric wind tunnel experiments. This was followed by a comprehensive study involving field measurements and wind tunnel tests by Stathopoulos et al. (1999) to further examine the wind loads on parapets themselves. Additionally, wind tunnel test studies conducted by Stathopoulos et al. (2002a, 2002b) focused on understanding the impact of the parameters related to geometry on wind loadings on parapets.

Over the past several years, extensive experimental research has been conducted to develop design wind guidelines for canopies attached to buildings. Specifically, Zisis and Stathopoulos (2010) and Candelario et al. (2014) focused on canopies attached to low-rise buildings, while Sakib et al. (2021) conducted wind tunnel experiments on canopies attached to medium- and high-rise buildings. The findings from these studies have played a pivotal role in establishing the current provisions for canopies, providing designers with specific design surface pressure coefficients and net pressure coefficients. For instance, Figure 4 highlights the net pressure coefficients derived from ASCE/SEI 7 (2022).

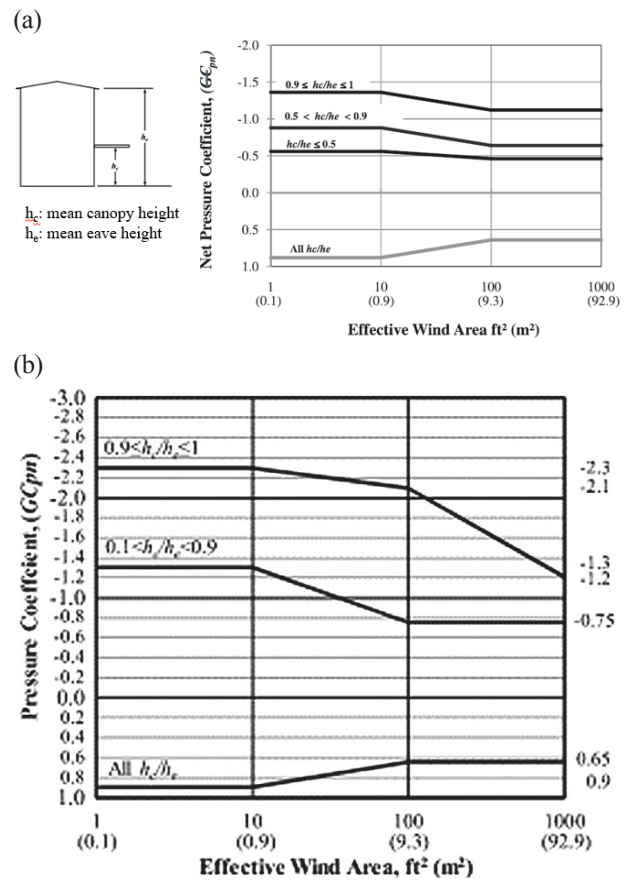


Figure 4. Net pressure coefficients for attached canopies on buildings based on mean roof height (h): (a) $h \leq 18.3$ m; and (b) $h > 18.3$ m (ASCE/SEI 7, 2022).

The wind loads on solar panels across various installations were investigated in studies conducted by Stathopoulos et al. (2014) and Alrawashdeh and Stathopoulos (2020, 2022, 2023b). These research endeavours aimed to gain insights into the effects of wind-induced loads on solar panels that are attached to building roofs, both in commercial and residential settings. Through the utilisation of wind tunnel tests, the researchers effectively quantified the wind loads and identified the key factors that govern the wind loads on solar panels, such as

building height, tilt angle, panel location, array clearance height above the roof and varying wind conditions, including the effect of geometric scale.

2.4. Terrain classification and exposure assessment

In the study conducted by Wang and Stathopoulos (2007), the focus was on examining the influence of upstream exposure on wind loading for low-rise buildings. Their research investigated how wind loads varied when transitioning over terrain with a single roughness change from smooth to rough as the wind approached the building. The data obtained from the study revealed an interesting trend. There was a rapid decrease in peak loads within an upwind patch length of approximately 250–500 metres, followed by stabilisation. These findings underscore the significant role of upstream exposure and the non-homogeneity of the upstream terrain in affecting wind loads on low-rise buildings.

In terms of determining the peak loads, Wang and Stathopoulos (2007) highlighted that the patch of length between 300 and 400 metres directly upwind of the building has the most significant influence. Building upon these observations, subsequent experimental and computational studies (Yu et al. 2019, 2021b, 2021) were conducted to develop an alternative and innovative method for estimating roughness length using Google Earth, showing promising results. A workflow diagram illustrating the procedure for estimating z_0 is provided in Figure 5.

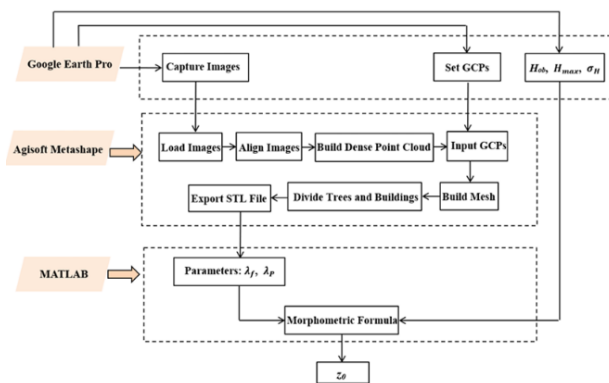


Figure 5. Roughness length (z_0) estimation process workflow (Yu et al., 2021).

3. Exploring future directions

This section of the paper discusses several key areas that warrant attention and further research, including non-synoptic wind effects on buildings; wind effects on permeable double skin façades towards the integration of BIPV and BIPV/T systems into buildings; performance-based wind engineering; and advancements in numerical methods for structural wind engineering.

3.1. Non-synoptic wind effects on buildings

Wind codes and standards are primarily developed for conventional wind conditions, specifically straight atmospheric boundary layer winds. While this approach aimed to establish a practical design framework that balances safety and economic considerations, it was not meant to overly simplify or idealise the actual conditions. However, recent developments have sparked significant interest in non-synoptic wind loads among professionals, researchers and wind code and standard committees. These developments are driven by the recognition of the need to enhance protection for life, socio-economic aspects, infrastructure and environmental considerations, focusing on resilience, sustainability and adaptation to climate change. Additionally, progress in research, coupled with an improved understanding of tornadoes and downbursts through physical and computational studies, has further propelled interest in non-synoptic wind effects (Stathopoulos and Alrawashdeh, 2020; Alrawashdeh and Stathopoulos, 2023a).

Though studies have applied laboratory modelling techniques to non-synoptic wind flows, respective field observations are currently missing. Such data would greatly benefit the ongoing progress in experimental and computational techniques in this area. Current research has mainly explored the dynamics of non-synoptic wind fields such as tornadoes and downbursts using both physical and numerical methods. Yet, there remains a significant need for further investigation into how these winds interact with surface roughness and topography. It is also critical to thoroughly assess newly suggested regulations for tornado-induced loads before any guidelines concerning downbursts are formulated. Hence, additional research in these areas is crucial.

3.2. Wind impacts on permeable double skin façades

The use of Permeable Double Skin Façade (PDSF) systems has been increasing in modern building designs due to their energy efficiency, improved indoor environmental quality and aesthetic appeal. The implementation of building-integrated photovoltaics (BIPVs or BIPV/Ts) into these systems further enhances the building’s energy sustainability, resilience and the ability to achieve zero-net energy; see Figure 6. While there are many studies available on the model, design, operation, and thermal and energy enhancements (e.g., Rounis et al., 2021, 2022), research on the structural integration and wind effects remains limited. Specifically, the wind effects on permeable PDSFs are not yet fully understood. Furthermore, the wind codes and standards still lack design guidelines for solar panels integrated flush on the building walls.

Research on wind pressure distribution, flow separation and pressure equalisation considering the influence of various design parameters such as cavity depth,

inlet size and configuration is essential for developing wind loading design guidelines and provisions.

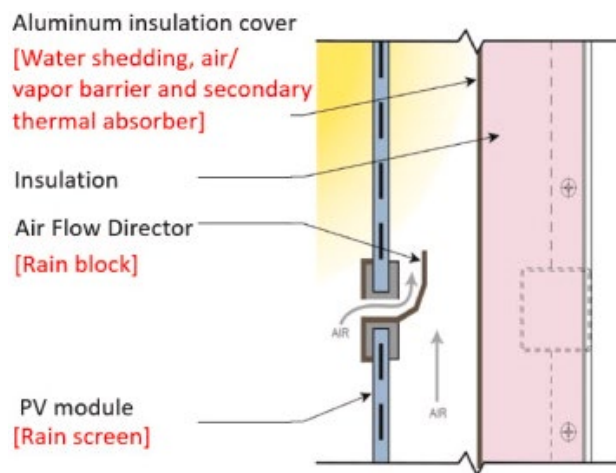


Figure 6. Cross-section of BIPV/T curtain wall components (Rounis et al., 2022).

3.3. Performance-based wind engineering

A performance-based design approach has been introduced for multi-storey steel buildings subjected to both wind and earthquake hazards (Athanasίου et al., 2022b, 2022). This approach utilises seismic ground motions and wind tunnel data to assess the performance of the building based on predefined criteria, such as repair costs. The approach was applied to the design of 12-storey and 16-storey concentrically braced frame (CBF) office buildings in Montreal, Canada, both of which satisfied collapse safety criteria under both earthquake and wind loading. The economic analysis, evaluated based on expected economic losses, revealed that wind-induced were more significant than seismic-induced losses. The findings indicate that this approach reduces the overly conservative nature of traditional wind design practices while promoting resilience against multiple hazards. However, there is need for further research to improve the accuracy and reliability of wind-resistant design methodologies, including the role of computational simulations and wind tunnel testing.

3.4. Advancement of numerical methods in wind engineering

There was a strong early intention to advance Computational Fluid Dynamics (CFD) methods (Baskaran & Stathopoulos, 1989, 1992, 1993; Bitsuamlak et al., 2006). However, the development of these methods was limited due to technological barriers. In recent research by Potsis and Stathopoulos (2022), a methodology for simulating incoming wind conditions within computational domains using large eddy simulation (LES) for the assessment of wind loads for low-rise buildings was developed. Wind tunnel experiments were conducted to characterise

turbulence features in the atmospheric boundary layer. The dynamic terrain method proposed in this study, which utilises velocity time histories derived from wind tunnel measurements, showed good agreement with theoretical and experimental data, making it suitable for low-rise building design. This approach is notable for its simplicity and time efficiency, making it attractive for practitioners.

Currently, wind codes and standards take a cautious approach when it comes to utilising numerical methods, especially Computational Fluid Dynamics (CFD), in the field of structural wind engineering. The NBCC (2020) explicitly states that CFD is not permitted for determining specified wind loads due to the lack of standards and the inability to verify its reliability and accuracy of the results. Also, the ASCE/SEI 7 (2022) acknowledges the need for similar standards for CFD as those established for Wind Tunnel Testing for Buildings and Other Structures (ASCE/SEI 49, 2021). It also emphasises the requirement for peer review and validation and verification (V&V) studies for every CFD analysis conducted. ISO 4354 (2009) highlights the limitations of CFD in accurately reproducing fluctuating flow characteristics and determining appropriate fractiles for extreme pressure coefficient values. Consequently, ISO 4354 (2009) recommends avoiding the utilisation of CFD until these limitations are satisfactorily addressed.

This discussion demonstrates that while most wind codes and standards acknowledge the potential of numerical methods, there is also a strong emphasis on the necessity of verification, validation and the establishment of specific standards for CFD applications. This underscores the significance of ongoing research and development efforts aimed at improving numerical modelling techniques to enhance the reliability and accuracy of computational wind engineering in the design practice of structural wind engineering applications.

4. Conclusions

Wind engineering continues to evolve and contribute to the safety, efficiency and sustainability of buildings and infrastructure. The research and advancements discussed in this paper provide valuable insights into the current state of the field and the future directions of wind engineering, particularly in the development of wind standards and codes of practice. Future challenges and opportunities will necessitate ongoing research and collaboration, which will be essential to deepen the understanding of wind effects and to refine design practices further.

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resilient and sustainable urban development, and addressing the challenges of climate change through adaptation strategies. He is also dedicated to developing and improving wind codes and standards.

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