

Article

Integrated Aerodynamic–Structural Validation Framework for Wind-Induced Load Assessment

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Abstract

Understanding wind–structure interaction (WSI) in low-rise buildings remains a significant challenge in wind and structural engineering, particularly under highly turbulent and non-stationary wind phenomena such as downbursts and tornado-like vortices. While Computational Fluid Dynamics (CFD) has become a widely adopted tool for predicting wind-induced loads, validation efforts remain predominantly limited to aerodynamic quantities—such as pressure and velocity fields—with insufficient consideration of structural response. This study presents a structured review of contemporary research in wind engineering, encompassing field measurements, wind tunnel experiments, and CFD modeling approaches. Particular attention is paid to turbulence model selection, methodological limitations of conventional validation strategies, and the often-overlooked necessity of incorporating structural response assessment into the validation process. Based on a synthesis of existing research, the paper outlines a multi-level validation perspective in which aerodynamic and structural validation are treated as interconnected components rather than independent procedures. The review identifies a prevailing focus on aerodynamic coefficients and flow field agreement, often lacking systematic integration of structural-scale verification. The proposed perspective emphasizes the need for a transparent and reproducible link between CFD-derived aerodynamic loads and structural response assessment. By bridging computational wind engineering and structural mechanics, this study supports a more reliable evaluation of wind-induced effects on building components and contributes to the development of robust, wind-resilient design methodologies for low-rise structures.

Keywords: computational fluid dynamics (CFD); wind engineering; low-rise buildings; turbulence models; extreme wind events



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1. Introduction

Wind-induced loading remains one of the governing design actions for low-rise buildings, particularly for roof systems and their structural components [1–3]. Local pressure peaks caused by atmospheric turbulence, flow separation, and vortex shedding may significantly exceed mean wind loads, leading to progressive damage or sudden failure of individual elements [4–7]. This issue becomes especially critical under extreme and non-stationary wind phenomena, such as downbursts and tornado-like vortices, where highly transient pressure fields and strong velocity gradients dominate the flow structure [8–10].

Over the past decades, extensive research efforts have been devoted to understanding wind–structure interaction through field measurements, wind tunnel experiments,

and numerical simulations. Field studies provide valuable insight into real atmospheric conditions but are often limited by measurement uncertainty, lack of repeatability, and restricted spatial resolution. Wind tunnel experiments offer controlled environments and repeatable conditions; however, they are subject to scaling effects and simplifications in terrain representation and structural detailing. As a result, computational fluid dynamics (CFD) has become an increasingly popular tool for predicting wind-induced pressures and flow characteristics around buildings.

Despite the rapid development of CFD methods and turbulence models, the validation of numerical simulations remains a critical challenge in wind engineering. Most validation studies focus primarily on aerodynamic quantities, such as pressure coefficients, velocity profiles, or flow patterns, often relying on wind tunnel or field data as reference benchmarks. While this approach provides confidence in the aerodynamic accuracy of CFD models, it does not fully address the question of how reliably numerically predicted loads translate into structural response, particularly at the component level.

In structural engineering practice, wind loads are ultimately assessed through their effects on structural elements, such as beams, connections, and roof components. However, the validation of CFD models rarely extends to this stage, and aerodynamic and structural analyses are typically treated as separate and sequential tasks. This separation introduces additional uncertainty, especially for elements exposed to highly localized loading, such as roof battens, rafters, or cladding components in low-rise buildings.

The present study addresses this gap by formulating a structured validation perspective that treats aerodynamic and structural verification as interconnected components of a continuous process. Based on a critical synthesis of existing research, the paper discusses how field observations, laboratory experiments, CFD simulations, and structural response assessment can be conceptually integrated within a unified wind–structure interaction framework. Rather than limiting validation to aerodynamic agreement alone, the analysis emphasizes the necessity of considering the entire load transfer chain—from wind flow characteristics to structural response indicators. This work represents a continuation of the author’s ongoing research on extreme wind phenomena and their impact on building structures. Previous investigations focusing on tornado-related flow fields and aerodynamic effects have revealed significant research gaps in the validation of numerical models at the structural level. Building upon these findings, the present study aims to systematize existing knowledge and outline a structured validation pathway that supports more reliable CFD-based assessment of wind-induced effects on low-rise building components [11,12].

2. Aerodynamic Characteristics of Wind Relevant to Engineering Applications

Wind loading acting on building structures is governed by complex aerodynamic phenomena occurring across a wide range of spatial and temporal scales. For engineering applications, these phenomena must be simplified into parameters that can be measured, modeled, and ultimately translated into design loads [13–17]. Understanding the aerodynamic characteristics of wind is therefore a prerequisite for reliable CFD modeling and subsequent structural assessment.

Table 1 summarizes key aerodynamic parameters relevant to wind engineering applications and highlights their typical sources, scales, and limitations. While these parameters are commonly used in both experimental and numerical studies, their applicability and interpretation depend strongly on the flow regime, terrain characteristics, and the type of wind phenomenon considered.

Table 1. Key aerodynamic and thermodynamic factors influencing wind–structure interaction.

Parameter/Mechanism	Physical Description	Effect on Structural Loads	Implications for CFD/Validation
Pressure gradients	Pressure changes over small distances in the boundary layer	Increased pressure and suction values; high local pressure peaks	High mesh resolutions required; RANS model sensitivity
Thermal convection	Lifting of warm air masses; formation of storm cells	Possible formation of high-energy microbursts	The need to take into account the changing properties of air
Humidity effects	The effect of water vapor on air density	Change in the value of effective loads	Calibration of models based on weather data
Turbulent kinetic energy (TKE)	Energy in the vortices of flow	Generating dynamic load changes	Requires SST, RSM, or hybrid models
Flow separation	Separation of the stream at the edges of the object	Extreme suction on roofs	k- ω SST models best represent the separation
Near-ground shear effects	Speed increases with altitude	Characteristic load on roofs and upper parts of walls	Realistic boundary conditions required (log law)
Rotational vortices	Local tornado-like vortices	Very high point suction	Validation from Tornado Tunnels/TTU and CFD data

2.1. Atmospheric Boundary Layer and Turbulence Characteristics

In natural conditions, wind flow affecting low-rise buildings develops within the atmospheric boundary layer (ABL), where velocity profiles, turbulence intensity, and length scales are governed by surface roughness, thermal stratification, and terrain morphology. For engineering purposes, the ABL is typically characterized using mean velocity profiles, turbulence intensity distributions, and integral length scales, which serve as fundamental inputs for wind tunnel experiments and CFD simulations [18].

Turbulence plays a critical role in generating fluctuating wind loads and local pressure peaks on building envelopes. Large-scale turbulent structures contribute to quasi-static loading, while smaller-scale eddies are responsible for high-frequency pressure fluctuations. Accurately representing this wide spectrum of turbulence remains a major challenge, particularly in numerical simulations, where turbulence models inherently involve simplifications and assumptions [19,20].

For CFD-based wind engineering applications, the representation of ABL turbulence must balance physical realism with computational feasibility. This trade-off has direct implications for the reliability of predicted pressure fields and, consequently, for the structural loads derived from these simulations.

2.2. Flow Separation, Vortex Formation, and Pressure Fluctuations

Flow separation and vortex formation are dominant aerodynamic mechanisms governing wind-induced loading on low-rise buildings. Sharp edges, roof ridges, and sudden changes in geometry promote flow detachment, leading to the formation of separated shear layers and coherent vortical structures. These features are responsible for localized suction peaks, particularly on roof surfaces and edge zones [21–24].

Pressure fluctuations associated with vortex shedding and reattachment processes exhibit strong spatial and temporal variability. In many cases, peak pressures significantly exceed mean values, making them critical for structural design and damage assessment.

Experimental studies have shown that these peak loads are often highly localized, emphasizing the importance of spatial resolution in both measurements and numerical models.

From a CFD perspective, capturing flow separation and vortex dynamics requires careful selection of turbulence models and numerical schemes. While Reynolds-averaged approaches can reproduce mean flow features, their ability to predict extreme pressure events remains limited, which directly affects the accuracy of load estimates used in structural analysis.

2.3. Non-Stationary and Extreme Wind Phenomena

In addition to synoptic-scale winds, low-rise buildings may be exposed to non-stationary and highly transient wind phenomena, such as downbursts, gust fronts, and tornado-like vortices. These events are characterized by rapid changes in wind speed, direction, and pressure, leading to loading conditions that differ fundamentally from those assumed in conventional design approaches.

Non-stationary wind events generate short-duration but intense pressure peaks, which can govern the response of lightweight structural elements and connections. Traditional aerodynamic descriptors based on stationary statistics may therefore be insufficient to describe the loading mechanisms associated with such events.

For CFD validation purposes, extreme wind phenomena pose additional challenges due to the scarcity of reliable field data and the difficulty of reproducing realistic flow conditions in laboratory environments. As a result, validation strategies often rely on partial or indirect comparisons, highlighting the need for broader validation perspectives that incorporate structural response considerations alongside aerodynamic agreement.

2.4. Engineering Interpretation of Aerodynamic Loads

In engineering practice, aerodynamic quantities such as pressure coefficients and velocity fields serve as intermediate parameters rather than final design outcomes. These quantities must ultimately be transformed into mechanical loads acting on structural elements. This transformation process introduces additional uncertainty, particularly when pressure fields exhibit strong spatial gradients or highly localized peaks.

For low-rise buildings, roof elements such as battens, rafters, and cladding components are especially sensitive to localized suction effects. The structural response of these elements depends not only on the magnitude of aerodynamic loads but also on their spatial distribution, duration, and temporal correlation.

Despite this, many validation studies focus exclusively on aerodynamic agreement between simulations and experiments, without assessing whether the resulting loads produce realistic structural behavior. This disconnect highlights the importance of extending aerodynamic validation toward structural response-based evaluation. The need for such an integrated perspective is further examined in the subsequent sections of this review.

3. Review of Wind Research Methods: Field Studies, Laboratory Testing, and CFD

Research on wind-induced effects on low-rise buildings has been conducted using a wide range of experimental and numerical approaches [25]. These methods differ significantly in terms of spatial and temporal resolution, controllability, scalability, and applicability to real structural systems. Tables 2–5 summarize the most commonly used approaches in field measurements, wind tunnel testing, CFD simulations, and structural response assessment, respectively, highlighting their key advantages and limitations.

While each approach provides valuable insight into specific aspects of wind–structure interaction, their partial scope often limits their ability to capture the complete load transfer

process from atmospheric flow to structural response. The following subsections review these methods in detail, with particular emphasis on their role in CFD validation and their potential integration within a unified validation framework.

3.1. Field Measurements

Field studies (full-scale measurements) constitute a fundamental source of knowledge on real wind–structure interactions, as they enable direct observation of aerodynamic phenomena under natural conditions, without the simplifications inherent in laboratory or numerical models. In the literature, such studies focus both on measurements of wind velocity and its turbulent characteristics, as well as on the recording of aerodynamic pressures and the structural response of buildings [26,27].

In the study *Examination of Wind Speed Based on Field Measurements on a Low-Rise Building*, detailed measurements of wind velocity and turbulence parameters were conducted on a residential building using roof-mounted and surrounding anemometers, enabling the analysis of local aerodynamic effects under natural exposure conditions. Similarly, Feng et al., in *Field Measurements of Wind Pressure on an Open Roof during Typhoons* [28], reported pressure measurements on open roof structures subjected to real typhoon events, providing valuable insight into transient and extreme loading scenarios. An important branch of field research also includes measurements of pressure coefficients on full-scale buildings. For example, *Full-Scale Measurements of Wind-Pressure Coefficients in Twin Medium-Rise Buildings* [29] investigated the influence of neighboring buildings and local microclimatic conditions on pressure distributions. Furthermore, studies presented at ICWE 2023 (*Field Monitoring of Wind Loads on “In-Service” Buildings* [30]) emphasize the importance of long-term monitoring for verification of code-based provisions and aerodynamic assumptions used in design standards. The literature also reports extensive field measurements on high-rise structures, such as studies conducted on the Shanghai World Financial Center, which provide data on turbulence structure, gust factors, and dynamic response under strong wind conditions. Although focused on tall buildings, such datasets are frequently referenced in comparative studies due to their detailed turbulence characterization and long-term monitoring records.

More recent contributions published in journals such as *Buildings and Fluids* further extend full-scale monitoring to urban environments, examining wind-induced pressures, façade loading, and atmospheric boundary layer characteristics in operational buildings. These studies highlight the increasing integration of sensor networks, long-term monitoring systems, and data-driven post-processing techniques in contemporary wind engineering research.

A summary of selected field studies is presented in Table 2, illustrating the diversity of investigated structures, wind phenomena, instrumentation systems, and measurement strategies.

Table 2. Key Summary of selected field studies in wind engineering.

No.	Article	Analyzed Phenomenon	Researched Object	Tools Used	Additional Comments
1	Examination of wind speed based on field measurements on a low-rise building [27]	Wind speed, turbulence characteristics	Low-rise building with rooftop PV	Rooftop and near-roof anemometers	Useful for near-roof flow characterization and small-scale structural elements
2	Field Measurements of Wind Pressure on an Open Roof during Typhoons [28]	Wind pressure under extreme events	Open roof structure	Pressure taps, anemometers	Rare full-scale data during typhoon passages

Table 2. Cont.

No.	Article	Analyzed Phenomenon	Researched Object	Tools Used	Additional Comments
3	Full-Scale Measurements of Wind-Pressure Coefficients in Twin Medium-Rise Buildings [29]	Pressure coefficients, shielding effects	Twin medium-rise buildings	Pressure sensors, weather station	Demonstrates influence of local microclimate
4	Field monitoring of wind loads on “in-service” buildings [30]	Wind loads and structural response	Operational buildings (Canada)	Long-term monitoring system	Verification of national building codes
5	Field Measurement of Wind Speeds and Wind-Induced Responses atop the Shanghai World Financial Center [31]	Wind speed, gust factors, structural response	Super-tall building	Anemometers, accelerometers	Combined aerodynamic and structural data
6	Field measurements of wind effects on a low-rise building with roof overhang during typhoons [32]	Pressure, turbulence, gust effects	Instrumented low-rise building	Pressure taps, meteorological sensors	Highly relevant for roof and edge effects
7	A Full-Scale Measurement of Wind Actions and Effects on a Sea-Crossing Bridge [33]	Wind actions, vibrations	Sea-crossing bridge	Anemometers, vibration sensors	Illustrates challenges of marine environments
8	Experimental Investigation of Local Wind Effects on Façade Scaffolding Structures [34]	Local wind speed amplification	Façade scaffolding	Field anemometry	Example of wind effects on temporary structures
9	Field measurements of boundary layer wind characteristics and wind-induced responses of super-tall buildings [35]	Boundary layer characteristics, response	Super-tall buildings	Multi-level anemometry	Useful reference for boundary layer profiles
10	Full-Scale Measurements of Wind and Pressure on an Instrumented Low-Rise Building subject to Typhoon Forces [36]	Wind speed, pressure, design loads	Low-rise building	Pressure sensors, anemometers	Direct comparison with code-based loads
11	Full scale measurements of wind effects on tall buildings [37]	Wind velocity, turbulence intensity, gust factors	High-rise building (full-scale)	Anemometers, accelerometers, long-term monitoring system	Provides high-resolution full-scale turbulence data frequently used for CFD validation benchmarks.
12	Field Measurement on Translational and Torsional Wind-Induced Response of a High-Rise Building during Typhoon Khanun [38]	Wind-induced structural response during typhoon	Full-scale high-rise building	Anemometers, accelerometers, structural monitoring system	Provides full-scale measurements of wind field and structural response during extreme wind events (typhoon conditions).

The review of field measurements clearly indicates that full-scale data provide irreplaceable reference information on the real structure of wind flow and its interaction with engineering structures. Studies conducted on low-rise buildings during extreme wind events are particularly valuable, as they allow for the analysis of phenomena that are difficult to reproduce faithfully in laboratory or numerical settings.

At the same time, limitations related to the control of measurement conditions and experimental repeatability mean that field data are most often used as part of a validation process rather than as an independent design basis. Consequently, field measurements play a crucial role in building confidence in CFD models and in assessing their ability to generate realistic aerodynamic loads. In many studies, such datasets serve as primary reference benchmarks for aerodynamic validation, forming an essential component of broader wind–structure interaction assessment strategies.

3.2. Laboratory Testing and Wind Tunnel Experiments

Laboratory studies, particularly experiments conducted in wind tunnels and extreme flow simulators, play a key role in the analysis of wind effects on buildings. They allow for controlled flow conditions, experimental repeatability, and detailed measurements of pressure distributions and aerodynamic forces acting on structural models [39].

In Wind tunnel test on low-rise buildings influenced by hillside height in typical mountain terrain [40], the influence of terrain topography on wind load distributions acting on low-rise building models was investigated, demonstrating significant modifications of the flow field resulting from terrain effects. In contrast, Experimental Study of Wind Pressures on Low-Rise H-Shaped Buildings [41] focused on the influence of building plan geometry on the spatial distribution and extreme values of aerodynamic pressures. A particularly important category of laboratory research involves experiments using tornado simulators. In Laboratory study of tornado-like loading on a low-rise building model [42], dynamic loads acting on building models exposed to tornado-like flows were investigated, enabling the analysis of phenomena that are difficult to capture in conventional wind tunnels. Similar issues are addressed in studies by Sabareesh et al. [43], where the dependence of pressure distributions on building geometry and vortex flow characteristics was examined.

Additional experimental studies have investigated the influence of roof geometry and flow separation mechanisms on wind-induced pressures in low-rise structures. For instance, detailed wind tunnel measurements on gable and hip roof configurations demonstrated the strong sensitivity of local suction peaks to roof pitch and edge effects, particularly in corner regions where flow separation and vortex formation dominate the pressure field.

Other laboratory investigations have focused on the interaction between surrounding terrain features and building aerodynamics. Experimental results indicate that upstream topography, obstacles, and building clusters may significantly modify local velocity profiles and turbulence intensity, leading to substantial variations in pressure coefficients even for geometrically identical structures.

The literature also includes methodological studies, such as the classic paper Wind tunnel simulation requirements to assess wind loads on low-rise buildings [44], which remains a key reference for the correct representation of boundary layer characteristics and turbulence in wind tunnel experiments. These methodological investigations emphasize the importance of reproducing realistic atmospheric boundary layer properties, including velocity profiles, turbulence intensities, and length scales, in order to ensure the physical relevance of wind tunnel experiments. Improper representation of these parameters may lead to significant discrepancies between laboratory measurements and full-scale wind behavior. A summary of selected laboratory studies, including their scope and key features, is provided in Table 3, enabling a concise comparison of applied experimental approaches.

Table 3. Summary of selected laboratory and wind tunnel studies in wind engineering.

No.	Article	Analyzed Phenomenon	Researched Object	Tools Used	Additional Comments
1	Wind tunnel test on low-rise buildings influenced by hillside height in typical mountain terrain [40]	Terrain-induced wind pressure and forces	Low-rise building models	Boundary layer wind tunnel, pressure taps	Highlights terrain–structure interaction effects
2	Laboratory study of tornado-like loading on a low-rise building model [42]	Tornado-induced pressure and dynamic loading	Low-rise building model	Tornado simulator, pressure sensors	Relevant for extreme wind scenarios
3	Experimental Study of Wind Pressures on Low-Rise H-Shaped Buildings [41]	Pressure distribution vs. geometry	H-shaped low-rise buildings	Wind tunnel, pressure measurement system	Demonstrates geometry-driven pressure variability
4	Wind tunnel simulation requirements to assess wind loads on low-rise buildings [44]	Simulation requirements, pressure accuracy	Generic low-rise building models	Atmospheric boundary layer wind tunnel	Foundational reference for tunnel methodology
5	Experimental and Numerical Estimation of the Aerodynamic Forces Induced by Wind Acting on a Fast-Erecting Crane [45]	Aerodynamic forces and validation	Crane model	Wind tunnel tests + CFD	Methodologically relevant despite different structure
6	Dependence of surface pressures on a cubic building in tornado-like flow [46]	Surface pressure in vortex-dominated flow	Cubic building model	Tornado simulator, pressure taps	Widely cited reference for vortex loading
7	Wind Tunnel Tests for Wind Pressure Distribution on Gable Roof Buildings [47]	Wind pressure on sloped roofs	Gable roof models	Wind tunnel pressure measurements	Direct relevance to roof elements
8	Dependence of surface pressures on building geometry and ground roughness [43]	Geometry and roughness effects	Building models	Wind tunnel experiments	Emphasizes boundary layer effects
9	Wind tunnel modeling and analysis of wind effects on low-rise buildings [48]	Comprehensive wind effects	Low-rise building models	Advanced wind tunnel instrumentation	Extensive dataset for validation studies
10	Experimental study of tornado-induced loads using large tornado simulator [49]	Extreme vortex-induced loads	Building models	Large-scale tornado simulator	Rare large-scale experimental facility
11	Evaluation of Wind Pressure Coefficients on Low-Rise Building Enclosures Using Modern Wind Tunnel Data [50]	External pressure coefficients on low-rise buildings	Gable-roof low-rise buildings	Boundary-layer wind tunnel database analysis	Shows that some code provisions may underestimate peak pressures.
12	Investigation of the Pressure Coefficients Correlation Field for Low-Rise Building Roofs. [51]	Spatial correlation of pressure coefficients	Low-rise building roof models	Boundary-layer wind tunnel, pressure sensors	Shows strong dependence of pressure correlation on wind angle and roof geometry.

The review of laboratory research clearly confirms its essential role in the analysis of wind–structure interaction, particularly for low-rise buildings and roof elements. Wind tunnel experiments enable systematic investigation of the influence of geometry, terrain configuration, and flow characteristics on pressure and aerodynamic force distributions, while maintaining high experimental repeatability.

At the same time, experiments conducted in tornado simulators reveal the specific nature of loads generated by rotating flows, which differ significantly from classical boundary-layer wind loading. The results of these studies indicate the potential underestimation of extreme loads in standard design procedures.

From the perspective of the present study, laboratory testing constitutes a key experimental reference for aerodynamic validation, enabling the connection of CFD simulation results with realistic aerodynamic load distributions. At the same time, their limitations in reproducing the full-scale structural response of building components justify the need to complement classical aerodynamic validation with structural validation, which is addressed in the subsequent sections of this article.

3.3. CFD Studies of Wind–Building Interaction

Numerical methods based on computational fluid dynamics (CFD) have become one of the primary tools for analyzing wind–building interaction over recent decades. Their growing popularity stems from the ability to represent detailed flow fields, analyze complex geometries, and achieve relatively low costs compared to field and laboratory studies [52–54]. In addition, continuous growth in computational power and the development of advanced turbulence models have significantly expanded the range of engineering problems that can be addressed using CFD simulations.

Review-type studies by Dagnew and Bitsuamlak (Computational evaluation of wind loads on buildings: a review [55]) and Blocken in 50 years of Computational Wind Engineering [56] provide comprehensive overviews of the development of numerical approaches in wind engineering. These works highlight the evolution of turbulence modeling strategies, numerical discretization methods, and best-practice guidelines for CFD applications in the built environment. At the same time, they emphasize persistent challenges related to grid sensitivity, boundary condition specification, and the accurate reproduction of atmospheric boundary layer characteristics.

Other authors have focused on practical aspects of applying CFD to wind load assessment. For instance, Thordal et al. [57] investigated the reliability of CFD simulations for predicting wind-induced pressures on buildings and emphasized the necessity of systematic validation against experimental data. Such validation is typically performed through comparisons with wind tunnel experiments or full-scale measurements, which serve as reference datasets for evaluating aerodynamic quantities such as pressure coefficients and velocity profiles.

Numerous comparative studies are also available in the literature, focusing on the influence of turbulence model selection on simulation accuracy. For example, several authors have evaluated the performance of commonly used Reynolds-averaged Navier–Stokes (RANS) turbulence models, including k – ϵ , k – ω SST, and Reynolds Stress Models (RSM), in predicting wind pressures on building surfaces. These investigations demonstrate that while CFD enables detailed predictions of velocity and pressure fields, the resulting aerodynamic quantities remain strongly dependent on modeling assumptions, mesh resolution, and numerical scheme selection. Studies applying CFD in the context of urban environments and pedestrian wind comfort are also noteworthy. Although their primary research objective differs from structural wind load assessment, they rely on similar numerical modeling principles and often provide valuable guidelines regarding grid

generation, turbulence modeling, and validation strategies. Consequently, methodological developments in urban wind studies contribute indirectly to improving CFD reliability in structural wind engineering. Recent studies also demonstrate the growing integration of numerical modelling with advanced data-driven techniques in building system analysis, including the use of virtual samples and machine learning methods for improving model reliability. A summary of selected CFD studies, including the scope of analyzed phenomena and structures, is presented in Table 4.

Table 4. Summary of selected CFD studies on wind–building interaction.

No.	Article	Analyzed Phenomenon	Researched Object	Additional Comments
1	Computational evaluation of wind loads on buildings: a review [55]	Wind loads, turbulence modeling	Buildings (various types)	Comprehensive review of RANS, LES and hybrid approaches
2	50 years of Computational Wind Engineering [56]	Development of CWE methods	Buildings and urban environments	Foundational reference for CFD best practices
3	Review for practical application of CFD for the determination of wind load on high-rise buildings [57]	Wind load assessment	High-rise buildings	Focus on practical modeling guidelines and validation
4	Study on Accuracy of CFD Simulations of Wind Environment around High-Rise Buildings [58]	Model accuracy, mesh sensitivity	High-rise buildings	Detailed comparison with wind tunnel data
5	A review of CFD simulations of wind flow around buildings for urban wind energy [59]	Wind flow patterns, turbulence	Buildings in urban context	Discusses CFD limitations and best practices
6	Evaluation of CFD Simulation Using Various Turbulence Models for Wind Pressure on Buildings [60]	Pressure coefficients (C_p)	Generic building models	Quantitative comparison of RANS models
7	CFD Numerical Simulation Analysis of Wind Load Based on BIM [61]	Wind loads, geometry complexity	BIM-based building models	Integration of CFD with design workflows
8	Numerical modeling of wind flow over a matrix of cubes [62]	Urban wind flow interaction	Arrays of cubic buildings	Benchmark study for urban CFD validation
9	Rigid and Aeroelastic Analysis of Wind Induced Flow Behavior Around Buildings using Numerical Techniques [63]	Aeroelastic effects	CAARC building	Combines aerodynamic and structural aspects
10	CFD simulations for evaluating pedestrian wind comfort [64]	Near-ground wind environment	Urban spaces and buildings	Methodology transferable to load assessment
11	A novel in situ sensor calibration method for building thermal systems based on virtual samples and autoencoder [65]	Sensor calibration and data-driven model validation in building systems	Building thermal monitoring system	Demonstrates the use of machine-learning techniques for improving reliability of measurement data used in simulation validation
12	CFD simulation of near-field pollutant dispersion in the urban environment: A review of current modeling techniques [66]	Urban wind flow and pollutant dispersion	Urban building configurations	Widely cited methodological review discussing best practices for CFD modeling of wind flow in built environments

Table 4. *Cont.*

No.	Article	Analyzed Phenomenon	Researched Object	Additional Comments
13	CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus [67]	Pedestrian-level wind comfort and safety in urban environments	University campus urban layout (Eindhoven University of Technology)	Presents a general decision framework for assessing pedestrian wind comfort and safety using CFD modeling
14	Investigation of Wind Pressure Dynamics on Low-Rise Buildings in Sand-Laden Wind Environments [68]	Wind pressure dynamics under sand-laden wind conditions	Low-rise building models	Investigates the influence of sand-laden wind environments on pressure fluctuations and aerodynamic loads on low-rise buildings

The review of CFD research clearly demonstrates that numerical methods have reached a high level of maturity and currently represent an indispensable tool for wind engineering analyses. Nevertheless, both review papers and comparative studies consistently indicate that CFD results remain highly sensitive to turbulence model selection, mesh quality, and the accurate representation of atmospheric boundary layer conditions.

An important conclusion emerging from the literature is that aerodynamic agreement between CFD simulations and wind tunnel measurements does not necessarily guarantee accurate prediction of structural response. In the majority of validation studies, comparisons are limited to aerodynamic parameters such as pressure coefficients, velocity distributions, or flow patterns. However, the ultimate engineering objective is to evaluate the structural effects of wind loading, including deflections, stresses, and load transfer mechanisms within structural elements. Consequently, despite the widespread adoption of CFD in wind engineering research and practice, there remains a clear need to extend traditional aerodynamic validation procedures toward approaches that consider the structural consequences of predicted loads. Addressing this methodological gap constitutes one of the key motivations for the research direction discussed in this study.

3.4. CFD Modelling of Tornado-like Wind Flows

Numerical simulations of tornado-like flows represent a specialized branch of CFD research in wind engineering, focused on the analysis of extreme, highly non-stationary, and rotating flow fields. Due to the complexity of the phenomenon, such studies most often employ Large Eddy Simulation (LES) models, which allow for a more realistic representation of turbulent structures [69].

Numerical investigations of tornado-like vortices commonly analyze different vortex structures, including single-cell and multi-cell configurations, in order to understand their influence on velocity distributions and local pressure maxima. Several studies have also focused on reproducing laboratory tornado simulators using CFD models, which enables direct comparison between numerical predictions and controlled experimental data.

An important research direction within this field concerns the analysis of tornado-induced loading on buildings. Numerical simulations have demonstrated that pressure distributions generated by rotating vortices may differ significantly from those associated with conventional straight-line winds. In particular, tornado-like flows can produce highly localized pressure peaks and complex load patterns on roof structures and building corners. Some studies further extend the analysis to debris transport and impact phenomena, which are directly relevant to structural safety and damage mechanisms during extreme wind events. A summary of selected numerical studies on tornado-like flows, including the

scope of analyses and the applied modeling approaches, is presented in Table 5 and serves as a reference point for further discussion of extreme wind effects.

Table 5. Summary of selected CFD studies on tornado-like wind flows.

No.	Article	Analyzed Phenomenon	Researched Object	Additional Comments
1	Numerical study of turbulent flow fields and the similarity of tornado vortices using LES [70]	Tornado vortex structure	Idealized tornado vortices	Classification of vortex types and similarity analysis
2	Numerical simulation of laboratory tornado simulator [71]	Tornado simulator flow	Laboratory tornado simulator	CFD–experiment comparison
3	Numerical study of wind pressure on low-rise buildings induced by tornado-like flows [52]	Wind pressures, forces	Low-rise building models	LES-based pressure distribution analysis
4	Numerical study on flow fields of tornado-like vortices using LES [72]	Flow field characteristics	Idealized tornado vortex	Validation against laboratory data
5	Numerical study of debris flight in a tornado-like vortex [73]	Debris trajectories	Tornado-debris interaction	Relevance to impact loading
6	Numerical Simulation of Tornado-like Vortices Induced by Small-Scale Cyclostrophic Wind Perturbations [74]	Tornado initiation mechanisms	Atmospheric-scale vortices	Modern CFD approach without physical simulator
7	An optimized numerical tornado simulator and its application to transient wind-induced response of a long-span bridge [75]	Structural response	Long-span bridge	Coupling CFD loads with structural response
8	Numerical Study of Tornado-Like Flow [76]	Velocity, pressure fields	Tornado generator model	Comparison with experimental generators
9	Simulating tornado-like flows: the effect of the simulator’s geometry [77]	Geometry influence	Tornado simulator	Combined experimental and CFD analysis
10	An innovative computational approach to generate tornado-like vortices using LES [78]	Boundary-driven tornado CFD	Idealized domain	Novel CFD generation strategies
11	Tornado-Induced Wind Loads on a Low-Rise Building [79]	Tornado-induced aerodynamic loads on buildings	Low-rise building model subjected to laboratory tornado-like vortex	Experimental investigation using a laboratory tornado simulator to measure pressure distribution and aerodynamic loads
12	Near-surface experimental exploration of tornado vortices [80]	Near-surface characteristics of tornado-like vortices	Tornado-like vortex generated in laboratory simulator	Experimental study focusing on velocity field, vortex structure and near-ground flow behaviour relevant for structural wind loading
13	Tornado-induced wind loads on a low-rise building: Influence of swirl ratio, translation speed and building parameters [81]	Influence of tornado vortex parameters on wind pressure distribution and aerodynamic loads	Low-rise building subjected to translating tornado-like vortex	CFD simulations investigating effects of swirl ratio, translation speed and building geometry on wind loads

The review of the literature on numerical tornado modeling clearly indicates that LES currently represents the standard approach for simulating tornado-like flows, enabling realistic representation of highly non-stationary turbulent structures. At the same time, most studies focus on reproducing flow fields and pressure distributions, with validation typically limited to comparisons with laboratory data obtained from physical tornado simulators.

A significant limitation of tornado-like analyses remains the lack of direct translation of aerodynamic results into measurable structural response of building elements, particularly for low-rise structures. Although some studies attempt to couple tornado-induced loads with structural response, this issue remains methodologically underdeveloped and requires further experimental–numerical research.

From a methodological perspective, the reviewed studies demonstrate that numerical simulations of tornado-like flows have achieved a high level of sophistication in representing complex flow structures and extreme aerodynamic loads. However, most investigations remain focused primarily on aerodynamic quantities, such as velocity fields and pressure distributions. The direct translation of these loads into structural response parameters—such as deflections, stresses, or connection forces—remains relatively limited in the literature. Consequently, future research should place greater emphasis on linking aerodynamic predictions with structural behavior, which may improve the reliability of wind-resistant design approaches for low-rise buildings and their structural components.

4. CFD Wind Modelling and Turbulence Model Selection

Modelling wind flow around buildings and within the near-ground layer using CFD methods constitutes a key stage in the aerodynamic analysis of structures exposed to environmental loading. Atmospheric flows in the vicinity of the ground surface are characterized by high turbulence intensity, pronounced spatio-temporal variability, and the presence of large-scale structures that dominate the turbulent kinetic energy (TKE) budget. Consequently, the selection of an appropriate turbulence model has a decisive influence on the reliability of predicted velocity fields, pressure distributions, and aerodynamic forces acting on building components [58,82–84].

In many engineering applications, an approach based on the Reynolds-Averaged Navier–Stokes (RANS) equations is commonly adopted. RANS-based modelling remains the standard in engineering CFD analyses of wind flows due to its numerical robustness and its ability to simulate very high Reynolds number flows at acceptable computational cost. This approach is widely recommended in the wind engineering and building aerodynamics literature, particularly for studies requiring multiple simulation variants and parametric comparisons.

4.1. Numerical Framework for Modelling Near-Ground Wind Flows

Flows within the near-ground layer are characterized by strong anisotropy of Reynolds stresses, a significant influence of surface roughness, and steep velocity gradients occurring over short distances from the ground surface. Realistic numerical representation of these phenomena requires the implementation of logarithmic or power-law wind velocity profiles, the consideration of high Reynolds numbers typical of atmospheric flows ($Re > 10^5$), and the ability to capture flow separation in the vicinity of roof edges and sharp geometric discontinuities.

In addition, the variability of pressure and velocity conditions resulting from the processes discussed in Section 2 necessitates the use of turbulence models capable of capturing both global flow trends and local, strongly nonlinear aerodynamic effects. In many CFD-based wind engineering studies, commercial solvers such as ANSYS

Fluent 2025 R1 are commonly employed, utilizing RANS-based formulations that have demonstrated good applicability for large-scale atmospheric flow simulations and provide a favorable compromise between computational accuracy and numerical efficiency.

4.2. Overview of Turbulence Models Used in Wind Engineering

Turbulence modelling in flows around architectural and engineering structures remains one of the principal challenges affecting the accuracy of aerodynamic load predictions. As demonstrated by Daróczy et al. in Comparative analysis of turbulence models for the aerodynamic simulation of H-Darrieus rotors [82], differences between turbulence models can lead to significant discrepancies in predicted velocity fields, pressure distributions, and turbulence intensity, particularly in regions dominated by flow separation and vortical structures [78,85,86].

4.2.1. Spalart–Allmaras Model

The Spalart–Allmaras model is a one-equation eddy-viscosity turbulence model originally developed for aerodynamic flows with moderate separation. Its primary advantages include low computational cost and good numerical stability, making it suitable for preliminary analyses and near-wall flow simulations with mild pressure gradients. However, numerous studies indicate that the simplified structure of the model limits its ability to accurately reproduce complex turbulent structures and extended separation zones typical of wind flow around buildings. As a result, while the model may provide reasonable pressure distributions on surfaces, its capability to reconstruct the full turbulent flow field remains limited and requires cautious interpretation of results [82,86,87].

4.2.2. k – ϵ Models

Two-equation k – ϵ models, particularly their realizable variants, represent one of the most commonly used tools in engineering CFD analyses of wind flows. The realizable formulation introduces modifications to the transport equations that improve model behavior in flows with large turbulent kinetic energy gradients and in regions of complex geometry. Xiong et al., in Study on Accuracy of CFD Simulations of Wind Environment around High-Rise Buildings [58], demonstrated that the realizable k – ϵ model provides good agreement with experimental data under certain flow conditions, especially at moderate wind speeds. At the same time, the authors emphasized that the assumption of turbulence isotropy may lead to underprediction of separation effects in more complex geometric configurations, a conclusion also supported by broader CFD reviews in wind engineering.

4.2.3. k – ω and SST k – ω Models

The k – ω model and its extension in the form of the Shear Stress Transport (SST) k – ω formulation were developed to improve the prediction of flows with strong separation and pronounced pressure gradients. The SST k – ω model combines the advantages of the classical k – ω formulation near walls with k – ϵ behavior in the free-stream region, enabling more realistic representation of boundary layer development and separation phenomena. Rezaeiha et al., in On the accuracy of turbulence models for CFD simulations of vertical axis wind turbines [83], demonstrated that SST k – ω models exhibit better agreement with experimental results than classical k – ϵ models, particularly in flows dominated by separation. Similar conclusions were drawn by Silva et al. in their analysis of aerodynamic interactions between neighboring buildings, where SST k – ω showed higher accuracy in predicting aerodynamic coefficients.

4.2.4. Reynolds Stress Models (RSM)

Reynolds Stress Models (RSM) solve the full set of transport equations for the Reynolds stress tensor, thereby eliminating the assumption of turbulence isotropy. In principle, this allows for more accurate representation of anisotropic turbulent structures and complex vortical interactions. In practice, however, RSMs are associated with high computational cost and increased numerical sensitivity, which limits their application primarily to comparative analyses or advanced validation studies rather than routine engineering wind flow simulations.

4.2.5. LES and Hybrid RANS–LES Approaches

Large Eddy Simulation (LES) methods and hybrid approaches such as Detached Eddy Simulation (DES), Delayed Detached Eddy Simulation (DDES), or Improved Delayed Detached Eddy Simulation (IDDES) offer significantly more detailed reconstruction of turbulent structures by directly resolving large-scale flow eddies while modelling the smaller scales. These approaches are capable of reproducing transient flow phenomena, vortex shedding, and complex separation patterns with considerably higher fidelity than steady RANS formulations. Nevertheless, numerous studies indicate that their application to full-scale building analyses entails extreme computational demands, the need for very fine near-wall meshes, and potential numerical stability issues at very high Reynolds numbers typical of atmospheric flows. Consequently, LES and hybrid RANS–LES approaches are most often applied in fundamental research, detailed studies of localized flow phenomena, or simulations of reduced-scale laboratory models. In practical wind engineering applications involving large computational domains or multiple parametric simulations, steady RANS models remain the most commonly used approach due to their favourable balance between computational cost and predictive capability.

4.2.6. Detached Eddy Simulation (DES) in Wind Engineering

Detached Eddy Simulation (DES) represents an intermediate modelling approach that combines features of Reynolds-Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) formulations. In DES methods, the near-wall region is typically modelled using a RANS formulation, while the outer flow region is treated using LES, allowing large turbulent structures to be resolved explicitly. This hybrid strategy significantly reduces computational cost compared to full LESs while still capturing important unsteady flow phenomena.

In wind engineering research, DES and its improved variants have been applied to study complex separated flows around buildings, bridge decks, and urban structures. These models have demonstrated improved capability in predicting transient vortex structures and fluctuating aerodynamic loads when compared with traditional steady RANS approaches. However, their successful application requires careful grid design and appropriate switching between RANS and LES regions, which may introduce additional modelling uncertainties.

Despite these challenges, hybrid RANS–LES approaches are increasingly considered a promising compromise between accuracy and computational feasibility. As computational resources continue to increase, their role in high-fidelity wind engineering simulations is expected to expand, particularly for studies focused on transient flow phenomena and extreme wind events.

4.3. Summary of Turbulence Model Selection for Wind Engineering Applications

Based on the reviewed literature, two-equation turbulence models—particularly the realizable k – ε and SST k – ω formulations—are frequently recommended for engineering

CFD studies of wind flows around buildings. The realizable k - ϵ model is often employed for preliminary analyses and parametric comparisons due to its numerical robustness and relatively low computational cost. In contrast, the SST k - ω model is commonly used when improved prediction of separation effects and boundary-layer behavior is required.

This combination reflects prevailing trends in wind engineering literature and provides a practical compromise between computational efficiency and predictive accuracy. Consequently, these models remain among the most widely applied turbulence formulations in CFD-based studies of wind effects on buildings and urban structures.

5. Proposed Multi-Level Validation Framework for CFD Wind Engineering Studies

The application of CFD methods in the analysis of wind–structure interactions requires not only the correct implementation of numerical models, but above all their systematic verification and validation [77]. While numerical modelling enables detailed analyses of flow fields and aerodynamic load distributions, without appropriate reference to real-world data its results remain only theoretical predictions. In wind engineering research, validation therefore represents a crucial step linking theoretical flow modelling, numerical simulations, and experimentally observed aerodynamic behavior of structures [78]. Based on the literature reviewed in the previous sections, this study proposes a conceptual validation framework for CFD-based wind engineering analyses. The framework integrates several complementary research approaches—including field observations, laboratory experiments, and numerical simulations—into a coherent workflow that improves the credibility and reproducibility of CFD results used in structural design studies.

5.1. Meaning and Importance of Validation

The literature distinguishes between two complementary but often confused concepts: verification and validation. Verification refers to the assessment of the numerical correctness of the solution of the governing equations, that is, to confirming whether the mathematical model has been solved in accordance with its formulation (e.g., through grid convergence studies, numerical scheme stability analysis, or discretization error assessment). Validation, by contrast, concerns the evaluation of the agreement between model predictions and the real behavior of the investigated physical phenomenon and requires comparison of simulation results with experimental data or field measurements.

In the case of atmospheric flows, the validation process is particularly demanding due to their spatial non-uniformity, unsteadiness, and limited repeatability of boundary conditions. Variability in wind direction and velocity, the influence of terrain roughness, large-scale turbulence, and thermal effects mean that full-scale field measurements rarely provide an ideal reference. Consequently, validation of CFD models in wind engineering requires a multi-stage approach that combines different experimental and numerical levels. From the perspective of wind engineering research, the distinction between verification and validation is particularly important because reliable numerical predictions require both mathematically correct solutions and consistency with physical observations.

5.2. Validation of Wind Models

Validation of CFD models used in wind interaction analyses is most commonly based on comparisons between selected aerodynamic quantities obtained numerically and the results of experimental investigations. The primary validation criteria include surface pressure comparisons, particularly peak pressure coefficient values, which directly determine the structural loading of roof and façade elements. Equally important is the comparison of

velocity fields, especially in regions of flow separation and within the near-ground layer, where the accuracy of the turbulence model plays a crucial role.

In addition to qualitative agreement of flow fields, quantitative error analyses are increasingly employed, using statistical measures such as the mean absolute error (MAE) and the root mean square error (RMSE). This enables an objective assessment of model accuracy and facilitates comparison of the performance of different turbulence models under identical flow conditions.

Contemporary approaches to CFD validation in wind engineering assume the necessity of a multi-level validation process, successively involving:

- Field measurements, which reflect real atmospheric conditions.
- Laboratory experiments conducted in wind tunnels, enabling controlled boundary conditions and experimental repeatability.
- CFD simulations, which integrate both data levels and allow parametric analyses.

Such a multi-level validation strategy significantly increases the credibility of CFD models by ensuring consistency between numerical predictions and experimentally observed aerodynamic phenomena. Nevertheless, most existing validation approaches remain focused primarily on aerodynamic quantities, such as pressure coefficients or velocity distributions, without fully addressing the final engineering objective of wind loading analyses—the structural response of building elements.

5.3. Why Structural Validation Is Necessary

In engineering practice, the ultimate outcome of wind action is not velocity fields or pressure distributions, but structural responses such as deflections, displacements, strains, and stresses in load-bearing elements. CFD models generate only aerodynamic loads acting on structural surfaces, whereas the actual response of a structure depends on its geometry, material properties, and the principles of solid mechanics [88–91].

For this reason, validation limited solely to the aerodynamic level is insufficient for a comprehensive assessment of model correctness in a design context. It is necessary to account for the coupling between wind-induced loads and structural response, which allows evaluation of whether numerically generated forces lead to realistic structural behavior consistent with elasticity theory.

For this reason, several authors have suggested extending traditional aerodynamic validation toward structural response-based assessment. In such an approach, aerodynamic loads obtained from CFD simulations are transferred to structural models, allowing the resulting displacements, stresses, or strains to be evaluated. This creates a direct connection between aerodynamic modelling and structural mechanics and enables assessment of whether numerically generated loads lead to physically realistic structural behavior. Based on the reviewed literature, the proposed validation framework can therefore be interpreted as a multi-stage workflow in which different research methods complement each other. Field measurements provide reference information on real atmospheric conditions, laboratory experiments enable controlled investigation of aerodynamic loads, and CFD simulations allow detailed parametric analyses of wind–structure interaction. When combined with structural response evaluation, such an integrated approach provides a more complete basis for validating CFD-based wind engineering models and improving their applicability in structural design.

6. Summary and Conclusions

This article presents a coherent analysis of research methods applied in wind engineering, with particular emphasis on their suitability for assessing wind effects on low-rise buildings and structural components. The literature review encompassing field measure-

ments, laboratory experiments, and CFD simulations made it possible to identify both the strengths of individual approaches and their limitations in the context of reliable prediction of aerodynamic loads.

Field measurements provide the most realistic data on actual wind conditions; however, their application in numerical model validation is limited by lack of repeatability, atmospheric non-uniformity, and difficulties in full control of flow parameters. Laboratory studies, conducted in wind tunnels or tornado-like simulators, enable systematic analysis of wind effects under controlled conditions, but require compliance with strict similarity criteria and careful interpretation of results when extrapolating to full-scale conditions.

CFD simulations currently constitute a key tool in aerodynamic analyses of building structures, offering high flexibility in terms of geometry, boundary conditions, and loading scenarios. The literature review indicates that despite the dynamic development of numerical methods, the accuracy of CFD predictions remains strongly dependent on the adopted turbulence model, ground layer modelling strategy, and the quality of validation. In particular, Reynolds-Averaged Navier–Stokes (RANS) models, such as the realizable k – ϵ and SST k – ω formulations, continue to represent a practical compromise between computational cost and the ability to reproduce key aerodynamic phenomena in engineering analyses of flows around low-rise buildings.

An important conclusion drawn from the literature analysis is that most validation studies focus on comparisons of velocity fields or pressure coefficient distributions, whereas the actual effect of wind on a structure manifests itself through its mechanical response. CFD simulations, as purely aerodynamic tools, generate distributions of aerodynamic loads that must ultimately be interpreted in terms of structural behavior. Therefore, the correctness of numerical predictions should also be assessed through the consistency of the resulting structural response with the principles of structural mechanics and elasticity theory. For this reason, validation based on measurements of deflections, displacements, or stresses in structural elements can be considered a natural extension of classical aerodynamic validation procedures.

The approach proposed in this study, involving the coupling of CFD simulations with experimental assessment of the structural response of a selected component of a low-rise building, aligns with the concept of multi-level validation incorporating field, laboratory, and numerical data. Such an approach enables not only evaluation of the quality of aerodynamic predictions, but also verification of their relevance from the perspective of structural safety and serviceability.

In conclusion, the presented review and adopted methodology indicate the need for a more integrated treatment of aerodynamic and structural aspects in analyses of wind effects on buildings. The results of this work provide a conceptual basis for further research aimed at developing CFD validation procedures based on measurable structural response. Such approaches may contribute to improving the reliability of numerical analyses in wind engineering and enhance their applicability in practical structural design. Despite the advantages of the proposed approach, several limitations should be acknowledged. The present study focuses primarily on wind effects on low-rise buildings and structural components under simplified aerodynamic conditions. Complex terrain effects, large-scale atmospheric variability, and highly transient extreme wind phenomena were not explicitly considered within the scope of this work.

Future research should therefore aim to extend the proposed validation framework by incorporating a broader range of structural elements, additional experimental datasets, and more advanced numerical modelling approaches. In particular, further studies integrating aerodynamic simulations with direct measurements of structural response may contribute

to the development of more reliable validation methodologies for CFD applications in wind engineering.

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