Chapter

Aerodynamics of Low-Rise Buildings: Challenges and Recent Advances in Experimental and Computational Methods

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Abstract

Buildings are bluff bodies, compared to streamline objects, such as airfoil. Wind flow over buildings leads to separation and hence a complex spatial and temporal mechanism that governs the nature and intensity of aerodynamic forces. This complexity mainly comes from the transient nature of incident turbulent winds and the fluctuating flow pattern in the separation bubble. The study of building aerodynamics is vital for the evaluation of cladding pressures, drag, shear, and uplift forces that are essential for safe and economic design. Flow separation makes it challenging to estimate loads without referring to direct physical and/or computational simulation. For several decades, aerodynamic testing has been employed for the estimation of wind pressures and forces on buildings. However, for residential homes and low-rise buildings, it has been always a challenge to predict full-scale pressures by traditional wind tunnel testing, as per the lack of large turbulence and Reynolds number effects, among other factors. The mismatch in flow physics makes it difficult to scale up wind-induced loads as the process can be highly nonlinear, which is the case when full-scale pressure coefficients do not meet those from small-scale aerodynamic testing. This chapter presents the challenges in the modeling and evaluation of aerodynamic forces on low-rise buildings, along with recent advances in both experimental and computational methods.

Keywords: aerodynamics, wind engineering, open-jet testing, wind tunnel, atmospheric boundary layer, low-rise buildings

1. Introduction

Researchers and engineering practitioners are attentive to understanding the behavior of structures under the effects of various loading patterns and conditions, to enhance their lifetime performance. Wind forces can threaten the safety of structures if their effects are underestimated; therefore, it is crucial to properly simulate and assess wind effects on civil engineering structures in order to achieve optimal and resilient designs that can maintain accessibility and functionality after natural disasters. Due to climate change and its consequences, the patterns of extreme winds and hurricane occurrence have been altered [1–3]. As a result, wind loads are becoming important in the analysis and design of buildings, especially in hurricane active regions. To put it into perspective, in most parts of the United States, especially in the east coast and the southern region, hurricanes and severe windstorms hit and bring widespread damage to buildings and other types of structures. The associated losses are estimated in billion dollars. The normalized hurricane-induced damage in the United States, between 1900 and 2005 (106 years of record), was estimated at about $10 billion (normalized to 2005 USD) [4]. Damage records totaling $265 billion were set by hurricanes Maria, Harvey, and Irma [5].

Due to the population growth, coastal zones are being more and more concentrated with residential buildings. These buildings are mostly light and low-rise, constructed from wooden materials, with different aerodynamic performance compared to high-rise buildings and residential homes. The American Society of Civil Engineers (ASCE) design standard defines a low-rise building to have an average roof height that is less than its lateral dimension; however the building should not exceed 18.3 m [6]. The majority of failures in low-rise buildings are reported because of strong wind effects on their envelope and specifically on roof panels [7]. **Figure 1(a)** shows a total failure of a low-rise building induced by hurricane Sandy in New York in 2012 [8]. The building envelope experienced significant loads from hurricane winds and lost its load path connections. In other scenarios, once part of a roof is breached during high winds, it facilitates the penetration of rainwater which can be harmful to interior properties and may cause serious problems to the building and loss of contents. **Figure 1(b)** shows severe roof damage during Hurricane Katrina in Lake Charles, New Orleans, in 2005 [9].

Examination of post-disaster surveys indicates initiation of damage through failure of roof components under extreme wind events. Earlier studies confirm the presence of extreme negative pressures at corners, ridges, and leading edges of roofs. The performance of roofs in low-rise buildings can differ significantly during a windstorm according to the shape of roof and its dimension. For instance, large roofs in industrial buildings may behave differently, compared to those of small roofs in a single-family low-rise building which can lead to different damage patterns to the building envelope [10–12]. In large roofs, the correlations among pressures acting at different roof locations are usually low [13]. In large roofs of light metal industrial buildings, leading edge failure usually occurs due to poor attachment of metal sheathing in areas that are exposed to uplift wind forces. This weakness eventuates to progressive peeling of the roof membrane causing further damage to the whole integrity of the building envelope.

The components and claddings in small roofs are usually exposed to damage during windstorms, due to local fluctuating negative pressures (uplift effects) due

(a) (b)

Figure 1.
Hurricane-induced damage: (a) complete collapse of a residential home induced by hurricane Sandy, New York, 2012 [8] and (b) severe roof damage by hurricane Rita in Lake Charles, in 2005 [9].

to flow separation, especially at roof edges and corners. **Figure 2** represents wind flow around a residential building [13]. The flow separates at sharp edges and re-attaches again in a fluctuating manner within the separation zones at a distance that is called separation bubble length, leading to uplift forces on the roof surface. The stagnation point is also specified in the windward wall, where the along-wind velocity is zero. **Figure 3** shows homes damaged by Hurricane Andrew in 1992 as a result of low pressures on the roof; and as a result, the shingles and sheathings were blown off due to high uplift forces. Referring to **Figure 2**, now it is shown that the separation bubble effects and the flow detachment are the main causes of these damage patterns of roof coverings which are a representation of roof areas under uplift forces. To fully understand windstorm effects on low-rise and residential buildings, it is essential to replicate the physics by experimental and computational methods. There are two important requirements: (1) correct reproduction of the main characteristic in the atmospheric boundary layer (ABL) and (2) aerodynamic testing at proper scales.

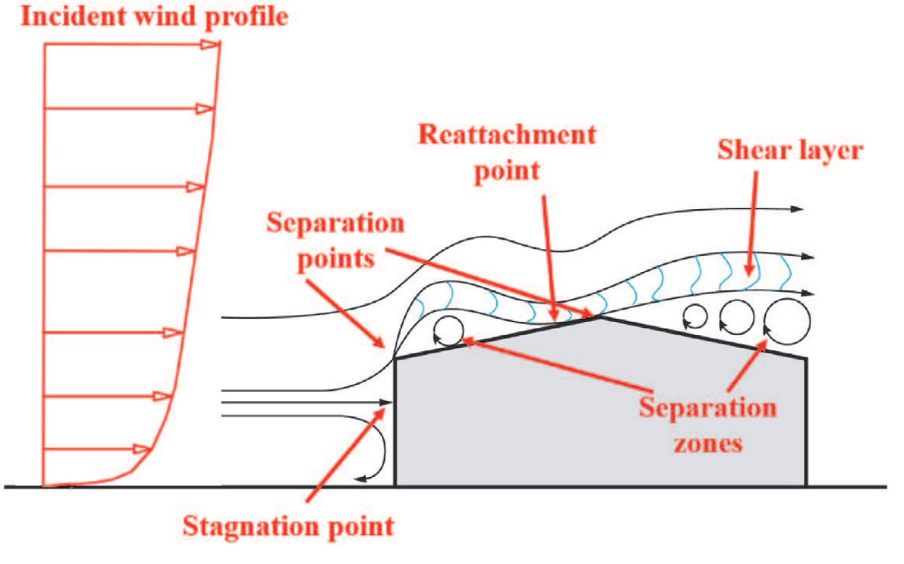


Figure 2.
Fluctuating flow separation and re-attachment (adapted from Ref. [14]).

Figure 3.
Homes damaged by hurricane Andrew in 1992 [15].

2. Atmospheric boundary layer characteristics

The variation of the mean velocity profile with height can be different over different terrain conditions depending on the friction effects from the earth's surface and the value of roughness length. **Figure 4** shows a schematic of different mean wind profiles over various topographical conditions of a dense urban area, suburban terrain, and over sea surfaces. In **Figure 4**, higher velocity is anticipated in lower altitudes on sea surfaces than the gradient wind in a dense city center.

After recording time series of wind velocity in the lab or in the field, the turbulence spectrum can be obtained accordingly. For the validation of the turbulence spectrum, theoretical spectra are usually used. The Kaimal spectrum is one of the widely used spectra, which is defined as follows [17]:

$$\frac{f\,S_{aa}(f)}{u_*^2} = \frac{An}{(1+Bn)^{5/3}} \tag{1}$$

in which f is nU/z. One can obtain the spectrum, S_{uu}, in the along-wind direction by considering A to be 105 and B to be 33 [14, 18]. For the lateral and vertical spectra, different values for the parameters A and B are suggested [14, 18].

The Engineering Science Data Unit (ESDU) spectrum is proposed based on a new von Karman spectrum, covering the full frequency range, as follows [19]:

$$\frac{f\,S_{uu}(f)}{\sigma_u^2} = \beta_1 \frac{2.987 n_u/\alpha}{\left[1+(2\pi n_u/\alpha)^2\right]^{5/6}} + \beta_2 \frac{1.294 n_u/\alpha}{\left[1+(\pi n_u/\alpha)^2\right]^{5/6}} F_1 \tag{2}$$

For more details regarding the ESDU spectrum and definition of different terms, readers are referred to Ref. [19]. The nondimensional cross-spectrum of u-component is defined in Ref. [20]:

$$\tilde{S}_u^c(\zeta,n) = \frac{S_u^c(\zeta,n)}{\sqrt{S_{uA}(n)}\sqrt{S_{uB}(n)}}, \tag{3}$$

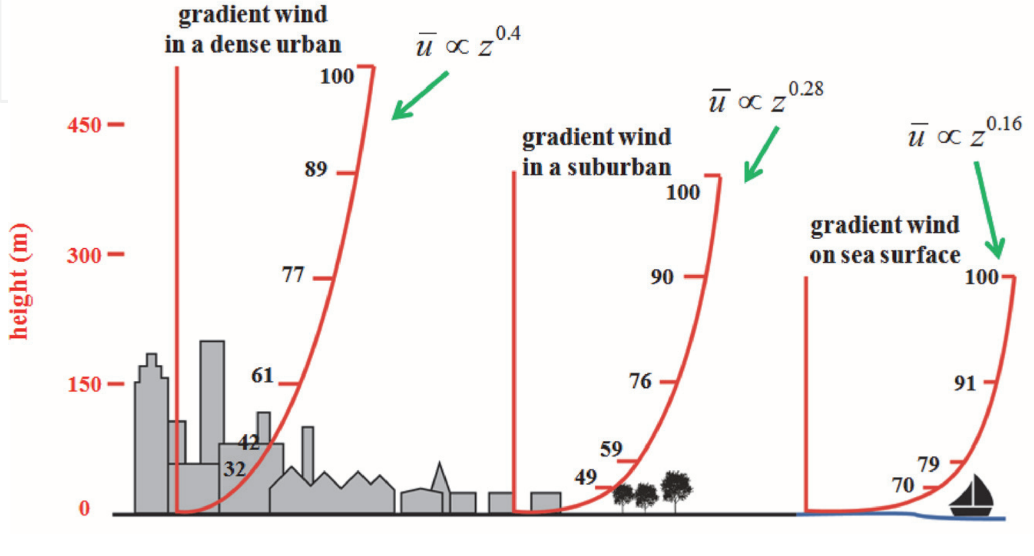


Figure 4.
Mean wind speed profiles over different terrains according to Davenport's power law profiles (adapted from Ref. [16]).

$$S_u^c(\zeta, n) = \int_{-\infty}^{\infty} R_u^c(\zeta, \tau) \exp(-j2\pi n\tau) d\tau. \tag{4}$$

where $R_u^c(\zeta, \tau) = E[u_A(t)u_B(t+\tau)]$, $S_{uA}(n)$, and $S_{uB}(n)$ are power spectra at two points, A and B, respectively; n is the frequency; and ζ is the distance between the two points A and B. The cross-spectrum of Davenport is defined in Ref. [21]:

Davenport:

$$\tilde{S}_u^c(\zeta, n) = \exp\left(-k_r \frac{|n\zeta|}{\overline{U}}\right), \tag{5}$$

Maeda and Makino:

$$\tilde{S}_u^c(\zeta, n) = \exp(-k_1\theta).(1 - k_2\theta^2), \tag{6}$$

where $k_r = 13(\zeta/z_m)^{0.4}, z_m = 0.5(z_A + z_B), \theta = \left\{(0.747\zeta/{}^xL_u)^2 + (2\pi n\zeta/\overline{U})^2\right\}^{1/2}$, k_1 = 1.0, and k_2 = 0.2 [20].

The integral length scale of turbulence, $L_u{}^x$, is a measure of the size of the largest eddy in a turbulent flow [18]. Having the time history of along-wind velocity component at any height, $L_u{}^x$ can be calculated using the approach described in Ref. [22]:

$$L_u^x = \left[\frac{E(f)U_{mean}}{4\overline{u}^2}\right]_{f\to 0} \tag{7}$$

where $\bar{u}$ is the standard deviation of the along-wind velocity component and $E(f)$ is the power spectral density. Studies show that the integral length scale of turbulence may decrease in the flow direction, due to the fact that larger eddies will usually dissipate energy into smaller eddies [23]. According to actual measurements, as the terrain roughness decreases, $L_u{}^x$ increases with the height above ground [18]. To quantify these changes, the integral length scale formulation suggested by ESDU is defined as follows [19]:

$$L_u^{ESDU} = 25z^{0.35}{z_0}^{-0.063} \tag{8}$$

And Counihan formulation used by Refs. [24, 25]:

$$L_u{}^C = 300(z/300)^{0.46+0.074\ln z_0} \tag{9}$$

3. Aerodynamics of low-rise buildings

Bluff body aerodynamics, and in particular fluctuating pressures on low-rise buildings immersed in turbulent flows, are associated with the complex spatial and temporal nature of winds [26]. This complexity mainly comes from the transient nature of incident turbulent winds, and the fluctuating flow pattern in the separation bubble. The flow in the separated shear layer is associated with fluctuations in the velocity field leading to the evolution of instabilities. The flow physics are dependent on upstream turbulence intensity, integral length scale, as well as Reynolds number. The later makes it difficult to scale up loads based on pressure and force coefficients as the process can be highly nonlinear, which is the case, for example, when full-scale pressure coefficients do not meet those from small-scale aerodynamic testing (**Figure 5**). Not only free stream turbulence impacts the flow pattern around bluff bodies, but also it can impact the thickness and length of the wake, hence significantly altering aerodynamic pressures.

In order to propose mitigation alternatives to minimize damages induced by windstorms to low-rise buildings, it is vital to understand how peak loads and spatial correlation of pressures are developed. As a first step to understand this mechanism, a true simulation of flow characteristics in accordance to real full-scale winds is necessary. There are common and valuable resources for the physical investigation of wind effects on structures, including small-scale wind tunnel testing, large-scale testing an open-jet laboratory, and full-scale field measurements.

According to Ref. [27], at relatively large-scale wind tunnel models, it is very difficult to model the full turbulence spectrum, and only the high-frequency end is matched [28]. For instance, as described in Ref. [29], more than 50% discrepancies in wind tunnel aerodynamic measurements are realized from six reputable centers for roof corner pressure coefficients and peak wind-induced bending moment in structural frames of low-rise building models. Therefore, selecting an appropriate testing protocol, including model scale ratio, for physical testing to minimize discrepancies in aerodynamic loads is essential. This can be achieved by considering constraints on laboratory testing that limits producing the large-scale turbulence and the inherent issues with limited integral length scale [30].

The literature raises questions regarding the adequacy of predicting full-scale pressures on low-rise buildings tested in flows that lack the large-scale turbulence. For instance, although a good agreement was observed between a wind tunnel testing on a generic low-rise building and full-scale data, discrepancies were shown in reproducing the largest of peak pressure near roof edges [31]. **Figure 5** shows minimum pressure coefficients at a building corner and eave level for the full-scale

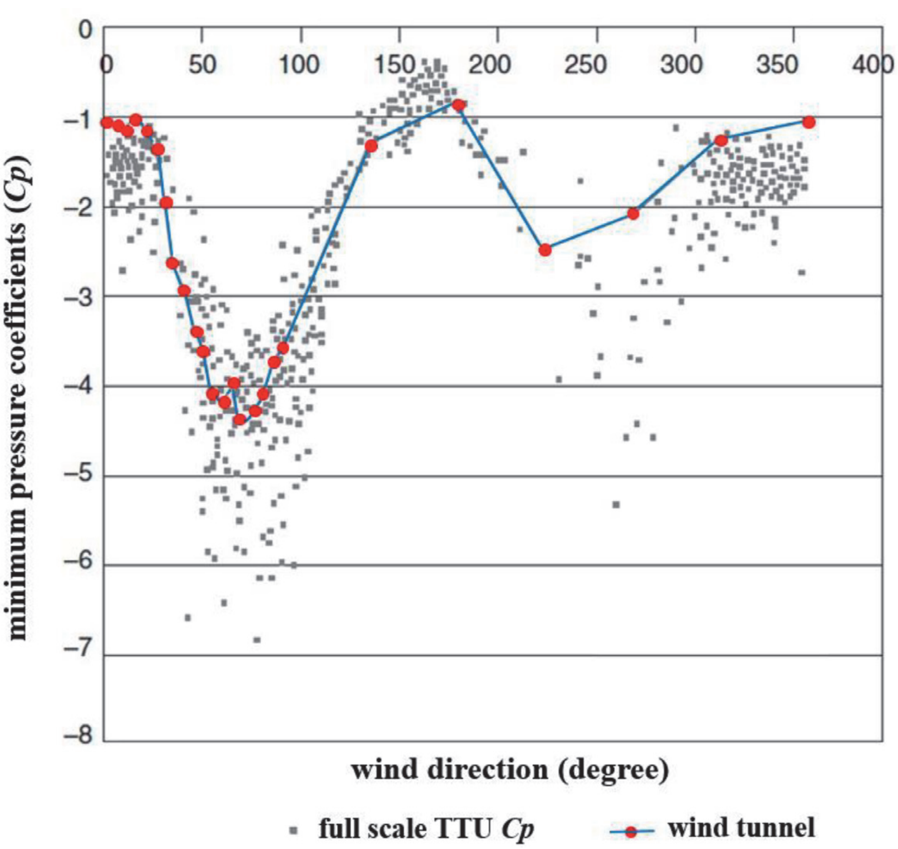


Figure 5.
Minimum pressures at building corner (adapted from Ref. [14]).

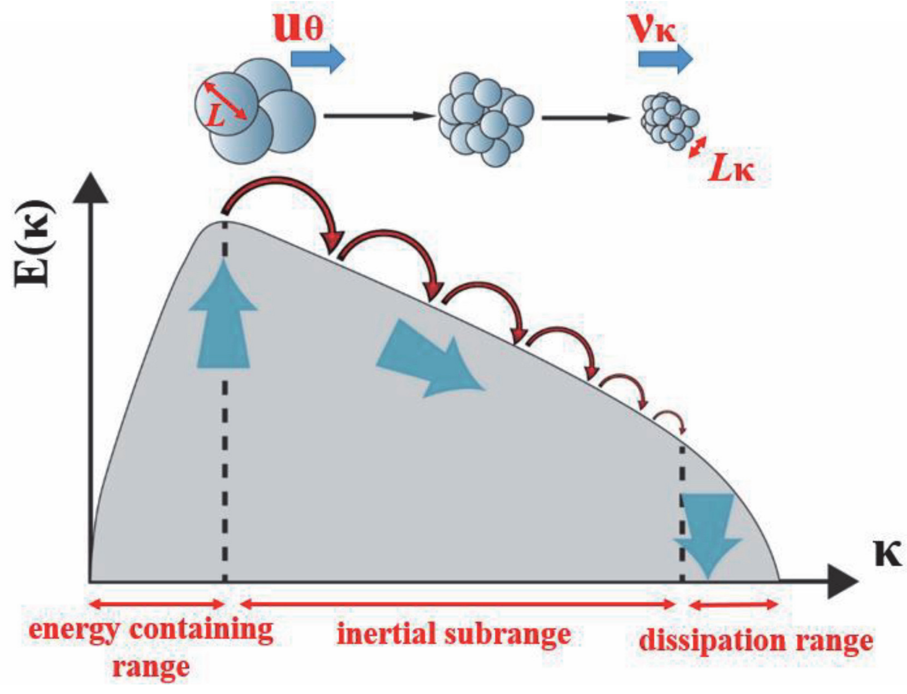


Figure 6.
Energy cascade in a turbulent flow (adapted from Ref. [32]).

Texas Tech University (TTU) experimental building, along with wind tunnel measurements [14]. The local peak pressures are weaker in wind tunnel testing than those at full-scale. For instance, at 65° wind direction angle, the wind tunnel reproduced minimum pressure coefficient of −4.3, while the full-scale field measurement is −6.8, and at 250° wind direction angle, wind tunnel shows −2.2, while the full-scale data shows −5.3. Therefore, there would be a major doubt on estimating the correct wind loads for design purposes based on wind tunnel testing. To describe this mismatch, first we need to define the concept of the energy cascade in a flow.

As depicted in **Figure 6**, the structure of a turbulent wind flow is constituted from a combination of large eddies and small eddies. In physical space, the large eddies are broken into smaller and smaller eddies with different spectral energy contents in various frequency ranges. In conventional wind tunnel testing, it can be challenging to appropriately reproduce low-frequency turbulence, which overwhelmingly contributes to the integral length scale and intensity of fluctuations. This leads to significant disparity among the wind tunnel flows and the target full-scale field flow conditions. As observed in **Figure 5**, this mismatch affected the local vorticity at edges and corners of a low-rise building model tested in a wind tunnel and resulted in local pressures weaker than those at full-scale. To alleviate these issues and to replicate the ABL flow characteristics for aerodynamics of buildings, advanced research in computational and experimental methods is essential.

4. Computational fluid dynamics in aerodynamics of buildings

In recent years, computational fluid dynamics (CFD) simulations have witnessed a spread use and applications as a potential tool in aerodynamic investigations of buildings. However, by considering the constraints of experimental testing in wind tunnels that limit producing the low-frequency large-scale turbulence and the inherent issues with limited integral length scale, implementing appropriate turbulence closure in CFD and developing a proper inlet transient velocity may alleviate the issues with experimental measurements in wind engineering. In CFD, the scale is not an immediate issue, as a full-scale model of the structure can be modeled and tested under various extreme wind scenarios. The simulation can be repeated to yield the same results any time. Even large-scale problems, such as simulating an urban area with condensed high-rise buildings for pollutant dispersion studies can be performed in CFD [33]; this can be challenging in laboratory testing due to scale issues.

CFD is gaining popularity within the wind engineering community along with the rise of computational power. Nowadays, CFD is commonly used to address wind engineering problems such as pollutant dispersion, wind comfort for pedestrians, aerodynamic loads on structures, or effects of bridge scour [34–37]. CFD-based numerical simulations will eventually complement the existing experimental practices for a number of wind engineering applications [38–40]. In most cases, numerical approaches are less time-consuming than experiments, and detailed information at higher resolution can be retrieved for scaled models from numerical simulations. In few earlier studies, the accuracy of analyzing bluff bodies with CFD has been questioned [41–43]. The reason behind inaccuracies was detachment of shear layer at sharp edges of bluff bodies. Detachment of shear layer makes the overall flow in the domain more responsive to local behaviors. The local effects are influenced by turbulence intensity and turbulence length scales of the incoming flow [36, 44]. Inaccurate replication of incoming turbulence properties in earlier studies was considered a reason for discrepancies in results. In Ref. [45], careful replication of horizontal turbulence properties at roof height of low-rise buildings was declared important. Few earlier studies focused on comparing surface pressures from numerical simulations with experiments and full-scale measurements. Good agreement was found among different data sources for mean pressure coefficient, while differences were found for fluctuating pressure coefficient [46].

Large eddy simulation (LES) can yield better results than turbulence closures that are based on Reynolds-Averaged Navier-Stokes (RANS), however, for higher cost of computations. The accuracy of solution of any wind engineering problem with CFD depends on the precise simulation of wind flow. A number of studies have indicated better performance of LES turbulence model for predicting mean and instantaneous flow field around bluff bodies [42, 47]. The concept of LES involves resolving the large scales in fluid flow and modeling the small scales. This approach is theoretically suitable for wind engineering applications as normally large scales are responsible for forces of interest [42]. Earlier applications of LES involving treatment of flows at low-Reynolds number yielded satisfactory results. Simply, the use of LES does not guarantee meaningful and accurate results. For flows with higher turbulence, results become more sensitive to the quality of the model [42]. Modeling of small-scale turbulence has gone through stages of improvement over the years. Sub-grid scale modeling remains the commonly used modeling technique. To yield accurate results, maintaining proper inflow boundary condition (IBC) is fundamental. Three methods are identified for generating IBC, and they are [48] (a) precursor database, (b) recycling method, and (c) turbulence synthesizing. The first two methods are computationally demanding; the third method is promising [49].

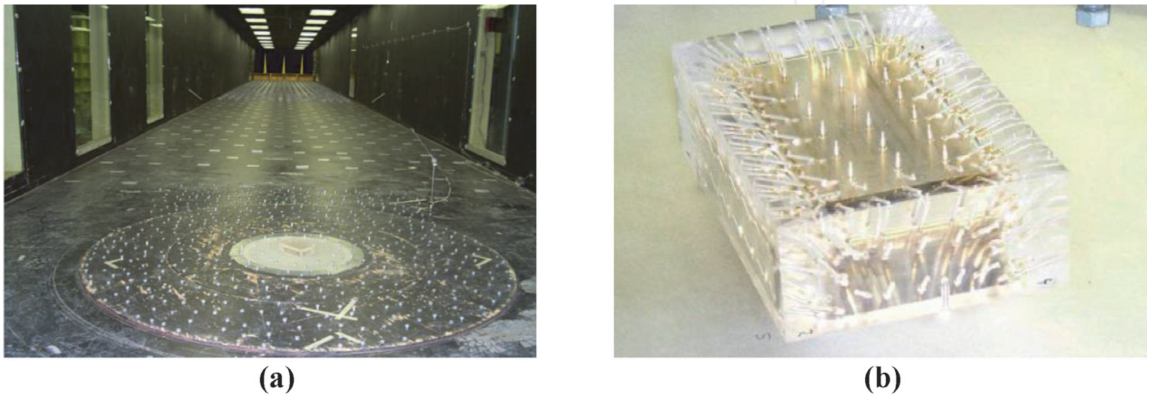
Maintaining horizontal homogeneity in the computational domain is another challenge in CFD simulations. Horizontally homogeneous boundary layer refers to the absence of artificial acceleration near the ground or stream-wise gradients in vertical profiles of mean velocity and turbulence intensity [50]. One may run steady-state simulation until it reaches convergence and monitors the vertical profiles of velocity and turbulence intensity at different locations in the domain. In case of LES, the mean value should be taken from the velocity time history for monitoring the vertical profiles. Achieving horizontal homogeneity ensures that the inlet, approach and incident flow are the same and eventually provide results with higher accuracy [50]. In several previously conducted studies, maintaining a consistent profile of mean wind speed and turbulent kinetic energy was an issue with different turbulence closure models. Significant near wall flow acceleration was found to cause unwanted change in mean wind speed and turbulent kinetic energy in simulation conducted in [51]. Additionally, issues in maintaining a consistent profile for turbulent kinetic energy were observed in [52, 53]. For accurate CFD results, maintaining consistent vertical profiles throughout the domain is important. Minor change in the profiles can create significant changes in the flow field. For flow around buildings, the importance of retaining the vertical flow profiles was stressed in Refs. [50, 54].

5. Aerodynamic testing

In Section 2, the main characteristics of ABL wind were presented. One of the main parts of any wind engineering study is to appropriately reproduce the wind characteristics in a controlled manner, to examine the response of a structure in the scope of a certain wind event. This means that first the wind flow characteristics should be simulated following an acceptable protocol and following that wind-induced pressures and loads on the surfaces of a building can be obtained by aerodynamic testing, according to the laws of similitude [55]. In order to satisfy these requirements, there are some tools used for ABL processes, including wind tunnels and open-jet facilities [56].

5.1 Wind tunnel testing

For several decades, wind tunnel modeling has been widely used as a technique to estimate wind-induced pressures and loads on buildings. **Figure 7** shows a view of a wind tunnel at the University of Western Ontario and a 1:100 scale low-rise building model. The arrangement and height of passive roughness elements are designed to reproduce wind flow over an open-terrain exposure with z_0 = 0.01 m [57]. This test case was selected benchmark for validation and comparison with other computational and experimental measurements. For accurate estimation of aerodynamic forces on buildings, proper replication of wind speed, turbulence intensity profiles, and spectral characteristics is essential [58]. Matching the spectral



(a) (b)

Figure 7.
A view of a wind tunnel at the University of Western Ontario: (a) 1:100 low-rise building model and the roughness element arrangement for an open-terrain exposure simulating z_o = 0.01 m *and (b) a closer view of the test model instrumented with pressure taps [57].*

content of real wind flow over the entire frequency range of interest has been a major challenge in laboratory testing [30]. Duplication of the entire range of spectral content requires equality of Reynolds number. In traditional wind tunnels, small-scale turbulence can be generated. For cases where incident flow contains only small-scale turbulence, the vortices are shed downstream before attaining maturity or before creation of maximum peak pressure. The increase in large-scale turbulence content in incident flow permits vortices to attain maturity, and as a result higher peak pressures on building models are obtained [59]. The low-frequency part on the turbulence spectrum corresponds to large-scale turbulence content of the incoming flow.

The gap between small and large wavelengths of velocity fluctuations (frequency domain), for real atmospheric flows, is larger than that in wind tunnel flows. It is challenging to duplicate both small and large scales of turbulence in wind tunnels due to the absence of Reynolds number equality [59]. Moreover, the neutral atmospheric boundary layer is scaled down in the order of 1:100 to 1:500 in wind tunnels. If low-rise buildings are scaled down in a similar proportion, additional problems may be encountered. The issues with too small test models are (a) inability to modeling structural details accurately, (b) lack of aerodynamic surface pressures at higher resolution, and (c) interference effects of measuring devices [59, 60]. In practice, larger test models with scales in the order of 1:50 are used to minimize these issues. This leads to mismatch in scaling ratio of the model and the generated boundary layer, which is responsible for difference in turbulence spectra in experiments and full-scale situation. The difference in turbulence spectra is considered to be a primary reason for the large variation in aerodynamic pressures on low-rise buildings for different wind tunnel experiments [60].

Several experiments have been conducted on scaled low-rise building models and heliostats over the past few decades. Large variation in tests has been attributed to difference in Reynolds number, turbulence spectrum, geometric scaling ratio, etc. While studying the influence of turbulence characteristics on peak wind loads on heliostats, wind tunnel tests were performed, the turbulence intensity and size of the largest vortices had a noticeable effect on peak pressures, compared to other parameters Reynolds number [61]. For solar panels, peak pressures in the wind tunnel were underestimated compared to full-scale data [62]. Geometric scaling is found to be a primary source of inconsistent results in wind tunnels with similar mean flow condition [60]. It was recommended to correctly model the high-frequency end of spectrum in order to obtain acceptable mean pressure coefficients. However, for accurate mean and peak pressures, the importance of replicating the entire turbulence spectra in large-scale testing was highlighted [27]. The size of the wind tunnel was held responsible for mismatch in the low-frequency end of the spectrum. High-frequency vortices are responsible for creating the flow pattern around bluff bodies, whereas low-frequency large eddies have higher influence on aerodynamic peak loads [63]. To conclude, in the case of low-rise buildings, it has been always a challenge, in wind tunnel testing, to properly simulate wind effects due to the lack of capability in turbulence modeling [56]. As a result, other concepts and tools such as open-jet testing were devised in recent years.

5.2 Open-jet testing

As part of developing ABL simulation capabilities, a small open-jet facility was built at the Windstorm Impact, Science and Engineering (WISE) research lab, Louisiana State University (LSU) (**Figure 8**). The concept of open-jet testing is that unlike wind tunnels, the flow has no physical boundaries which has two main advantages: (i) larger eddies can be produced, leading to higher peak pressure coefficients, similar to those at full scale, and (ii) minimum blockage can be

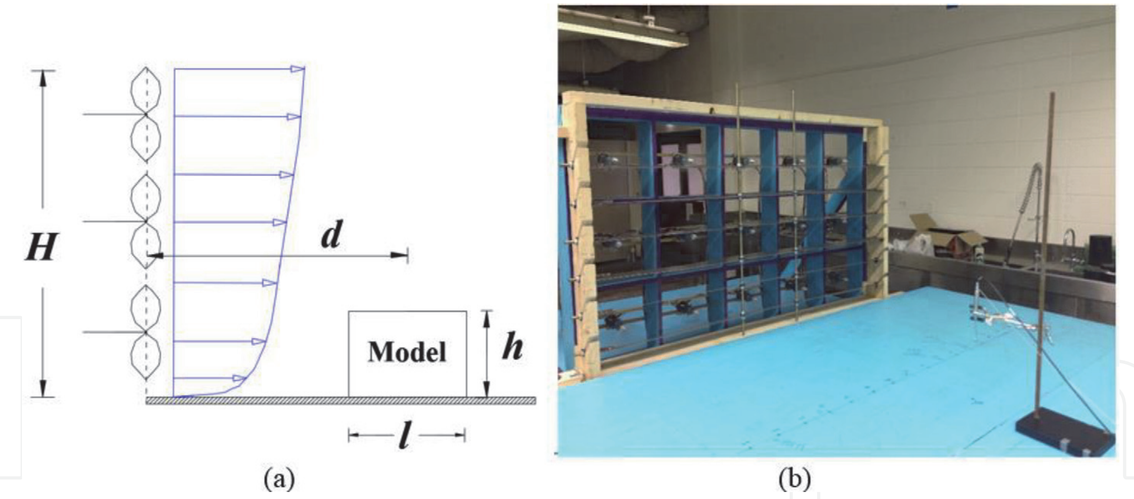


Figure 8.
The concept of open-jet testing: (a) test model located at an optimal distance from the blowers' exit and (b) 15-fan small open jet at LSU.

Figure 9.
LSU WISE small open-jet hurricane simulator (with adjustable turbulence and profile production mechanism): (1) general view of testing setup, (2) section model test specimen, (3) cobra probes for measuring 3-component wind velocities, (4) ZOC23b miniature pressure scanner, and (5) lap top computer with software for data collection and processing.

achieved. The aim was to physically simulate hurricane wind flows with similar characteristics to those of open and suburban terrain. Small-scale models of low-rise buildings were tested to examine how the turbulence structure of the approaching flow, scale issue, and open-jet exit proximity effect can influence the flow pattern on low-rise buildings and alter the separation bubble length on the roof surface. Specifically, the aim was to understand how these parameters affect the values of peak fluctuating external pressures on the roof surface [58, 64]. With an adjustable turbulence producing mechanism, different wind profiles are physically simulated. In addition, this lab has cobra probes, load cells, laser displacement sensors, and a 256-channel pressure scanning system (**Figure 9**).

A facility capable of testing low-rise buildings at full-scale would be ideal, if the artificial flow is also at full scale, which is difficult to achieve. A 1:1 scale flow that mimics real hurricane characteristics at full-scale would need giant blowers located at a distance that is significantly far than what a feasible facility can afford. Artificial wind contains significant high-frequency turbulence with limitations on the large-size vortices that make scaling buildings unavoidable, if we were to replicate correct physics. There are some testing capabilities that can engulf full-scale residential homes; however, the flow characteristics raises important questions about their similarity to those at full scale. This said, scaling residential homes is essential to maintain correct physics, and at the same time large-scale testing (not full-scale) will lead to improved Reynolds number. Large-scale wind testing went through several phases before reaching the present stage [63]. A multidisciplinary LSU research team from Civil and Environmental Engineering, Mechanical Engineering, Coast and Environment, Louisiana Sea Grant, Geography and Anthropology, Construction Management, and Sociology collaborated on a project titled "Hurricane Flow Generation at High Reynolds Number for Testing Energy and Coastal Infrastructure" that was awarded by the Louisiana Board of Regents to build Phase 1 of a large wind and rain testing facility (**Figure 10**). Phase 1 permits generating wind flows at a relatively high Reynolds number over a test section of 4 m × 4 m. These capabilities enable executing wind engineering experiments at relatively large scales. Moreover, the large open-jet facility has a potential for conducting destructive testing on models built from true construction materials. Blockage is minim, as per the concept of open-jet testing [65]. This state-of-the-art facility can generate realistic hurricane wind turbulence by replicating the entire frequency range of the velocity spectrum.

The large LSU WISE open-jet facility enables researchers to test their research ideas; to expand knowledge leading to innovations and discovery in science, hurricane engineering, and materials and structure disciplines; and to build the more resilient and sustainable infrastructure. The facility will enable scientists and researchers to test potential mitigation and restoration solutions, both natural (e.g., vegetation) and artificial. Potential applications include, but are not limited to, wind turbines, solar panels, residential homes, large roofs, high-rise buildings, transportation infrastructure, power transmission lines, etc. Testing at this facility can provide knowledge useful for homeowners and insurance companies to deal more effectively with windstorms, for example, to fine tune design codes and give coastal residents options for making their dwellings more storm-resistant. The goal is to build new structures and retrofit existing ones in innovative ways to balance resilience with sustainability, to better protect people, to enhance safety, and to reduce the huge cost of rebuilding after windstorms. In addition, the facility offers tremendous education value to k-12, undergraduate, and graduate students at a flagship state university, designated as a land-grant, sea-grant, and space-grant institution. This will broadly impact the wind/structural engineering research and

Figure 10.
LSU WISE large testing facility (with a test section of 4 m × 4 m).

education field and facilitate effective investments in the infrastructure industry that will result in more resilient and sustainable communities and contribute to economic growth and improve the quality of life.

6. Sample study of building aerodynamics at the LSU WISE lab

The LSU research team aspires to match the spectral content of real wind using large-scale open-jet testing and CFD simulations in their quest of accurate estimation of peak pressures on building surfaces under wind. The goal is precise estimation of peak pressures on buildings through the generation of large- and small-scale turbulence via open-jet testing as well as advanced CFD simulations. Extreme negative pressures near ridges, corners, and leading edges of roofs are governed dominantly by wind turbulence and Reynolds number, among other factors. Both small- and large-scale turbulence vortices are responsible for peak pressures and can influence separation in the shear layer. This demands for precise replication of wind speed profile, turbulence intensity profiles, and spectral characteristics. Replication of the true physics requires higher Reynolds number which is difficult to achieve in wind tunnels. In traditional wind testing, it is challenging to create large-scale turbulence. An increase in large-scale turbulence content in incident flow allows vortices to attain maturity, and as a result higher peak pressures can be reproduced. A fundamental research objective, however, is to address the challenge of replicating real wind turbulence experimentally and computationally. Resolving the scaling issue by investigating larger test models at higher Reynolds number is another highlight of our research at the LSU WISE lab.

The velocity was measured at different heights in the open-jet facility with cobra probes to obtain the mean velocity and turbulence intensity profiles. **Figure 11(i)** shows the comparison of experimental mean velocity profiles from LSU open jet and TPU wind tunnel with theoretical wind profiles measured for open terrain condition ($z_0 = 0.01\,m$). It was observed that the measured mean velocity profile at LSU open jet was consistent with different theoretical profiles and also velocity profile measured at TPU. It should be noted that the U_{ref} corresponding to 10 m in full scale was 22 m/s [66]. For normalizing the experimental data, velocity information corresponding to $H_{ref} = 0.75$ m was considered. Mean velocity corresponding to 0.75 m was considered to be U_{ref} in the open jet. **Figure 11(ii)** shows along wind turbulence intensity profiles from experimental data and theoretical formulations. The velocity data were processed to obtain turbulence intensity, and the profile was compared with theoretical profile corresponding to the following equation.

$$I_u(z) = \frac{1}{\ln\left(\frac{z}{z_0}\right)} \tag{10}$$

The vertical profile plot for turbulence intensities shows that the LSU open-jet facility has approximately 20% turbulence intensity at reference height. Both mean velocity and turbulence intensity profiles in **Figure 11** shows that LSU open-jet facility is capable of replicating open terrain near-ground ABL flow.

A scaled (1:13) cubic building model was tested at the LSU WISE large open-jet facility. The primary objective of this task was to compare surface pressure coefficients those obtained by wind tunnel testing on a smaller scale (1:100) model. Wind tunnel measurements are obtained from the published dataset of Tokyo Polytechnic University (TPU). The building model was instrumented with several pressure taps to capture surface pressures. A total of 64 taps were distributed on roof, same as the

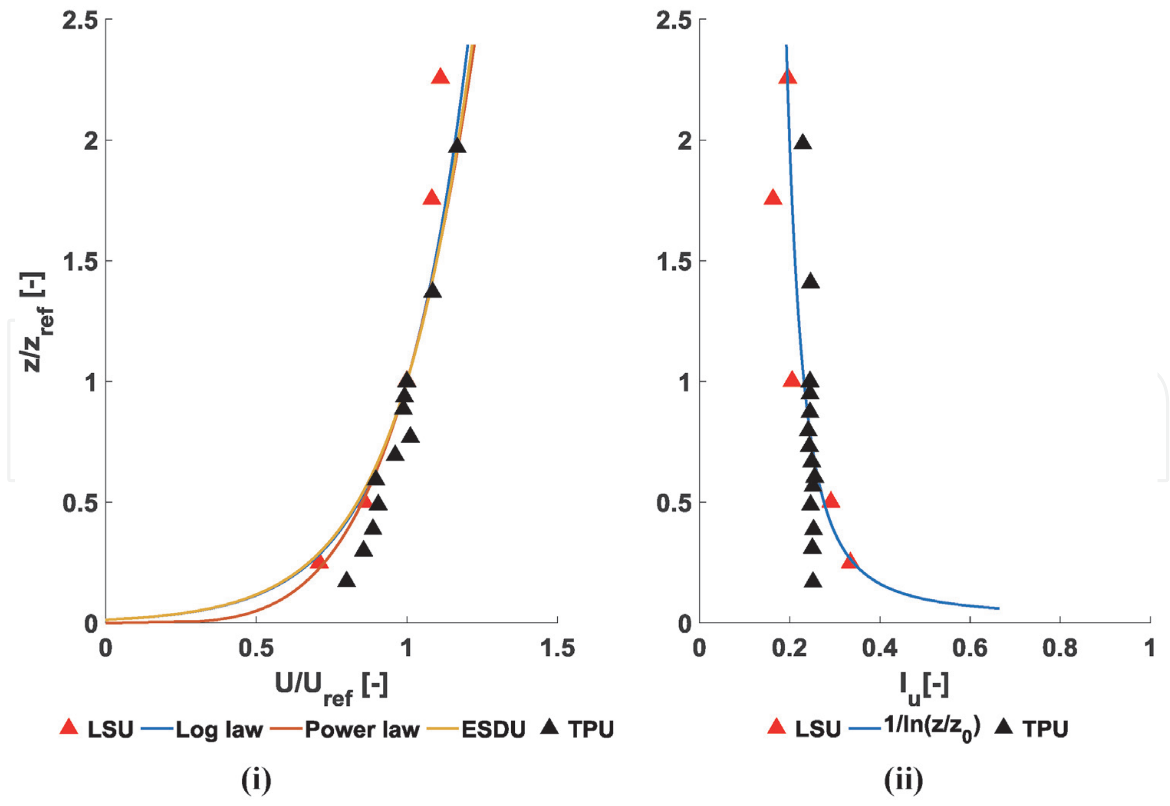


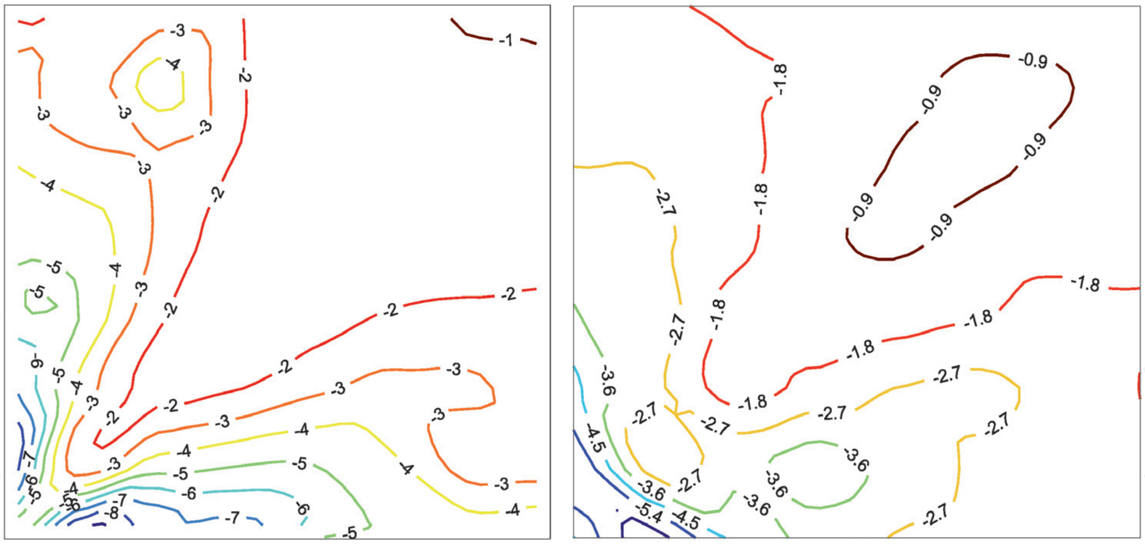
Figure 11.
Flow characteristics: (i) mean velocity and (ii) turbulence intensity.

TPU wind tunnel model. Pressure taps were connected to Scanivalve pressure scanners through appropriate tubing. Two cobra probes were used to monitor upstream velocity at roof height [58]. The following equation was used to compute the pressure coefficient.

$$C_p(t) = \frac{p(t) - p_s}{\left(\frac{1}{2}\right)\rho U^2} \tag{11}$$

The time history of pressure coefficients, $C_p(t)$, was obtained from the pressure time history, $p(t)$, recorded using pressure scanners. The static pressure p_s was considered reference for the pressure transducers. In addition, base line pressures were collected before and after each experiment. Once the time history of pressure coefficients was obtained, statistical analysis was done to obtain mean, minimum, and root mean square (rms) values. Measurements from LSU open-jet and TPU wind tunnel were processed the same way. The maximum and minimum values were obtained using MATLAB functions with a probabilistic approach described in Ref. [67]. This approach was considered, to account for the highly fluctuating wind flow, to yield a more stable estimator of peak values.

Sample of the findings of the experiment and comparison with TPU results is shown in **Figure 12**. The distribution of pressure coefficients obtained by open jet testing is symmetric like what is observed in the TPU wind tunnel testing. Since the model in open jet was tested at a higher Reynolds number, higher values of peak pressure coefficients are realized. Higher suction was observed near the zone of flow separation on the roof. Stronger suction for open-jet testing was found due to higher Reynolds number in open-jet and the presence of larger-scale turbulence compared to the wind tunnel. This difference in Reynolds number leads to difference in formation of flow separation zone, stagnation point on windward face, and the reattachment length. The difference between full-scale and reduced-scale wind tunnel tests is owed to similar reasons.



(a) (b)

Figure 12.
Minimum pressure coefficients on roof: (a) LSU open-jet (b) TPU wind tunnel (wind from bottom left corner).

On the computational side, the k- SST turbulence model was employed for improved mean pressure prediction near the flow separated region. An advanced approach is ongoing that employs large eddy simulation (LES) to generate accurate mean and peak pressures. **Figure 13** shows a sample of high-quality mesh and CFD simulations in OpenFOAM.

In order to alleviate the challenges and shortcomings involved within the experimental tests in boundary-layer wind tunnels, in recent years, CFD was considered as an effective tool for the simulation of wind effects on civil engineering structures. However, it is necessary that the numerical CFD model would be capable of generating turbulence in a flow with certain spectral contents and eventually to reproduce peak pressures on building surfaces. The objective of this research is therefore to provide a basis for the development of recommendations and guidelines on using a CFD LES model that enables appropriate simulation of turbulence spectra of ABL inflow and reproducing the peak wind pressures on the roof of low-rise buildings. **Figure 14** represents a schematic of the tools used by Aly and Gol Zaroudi [49] to simulate peak wind loads on a benchmark full-scale building from the Texas Tech University (TTU) in an open-terrain field. The details, advantages, and disadvantages of each tool are discussed in Aly and Gol Zaroudi [49].

Considering the current rapid improvements in developing high-speed processors that can run in parallel on high-performance computing (HPC) clusters and devising new digital storage devices with huge capacities, CFD is becoming a promising tool in wind engineering applications. However, it is still a challenge for proper simulation of turbulence according to ABL wind characteristics and accurately reproducing peak pressures on low-rise buildings, even with supercomputers [40]. Aly and Gol Zaroudi [49], therefore, attempt to address some of the challenges in experimental and numerical simulations for aerodynamic testing of low-rise buildings, to reproduce realistic peak pressures. The study focused on wind flow processes in CFD with an objective to mimic full-scale pressures on low-rise building. The study implemented CFD with LES on a scale of 1:1 building. After a proximity experiment was executed in CFD-LES, a location of the test building from the inflow boundary was recommended, different from existing guidelines (RANS-based, e.g., COST and AIJ). The inflow boundary proximity showed significant influence on pressure correlation and the reproduction of peak pressures.

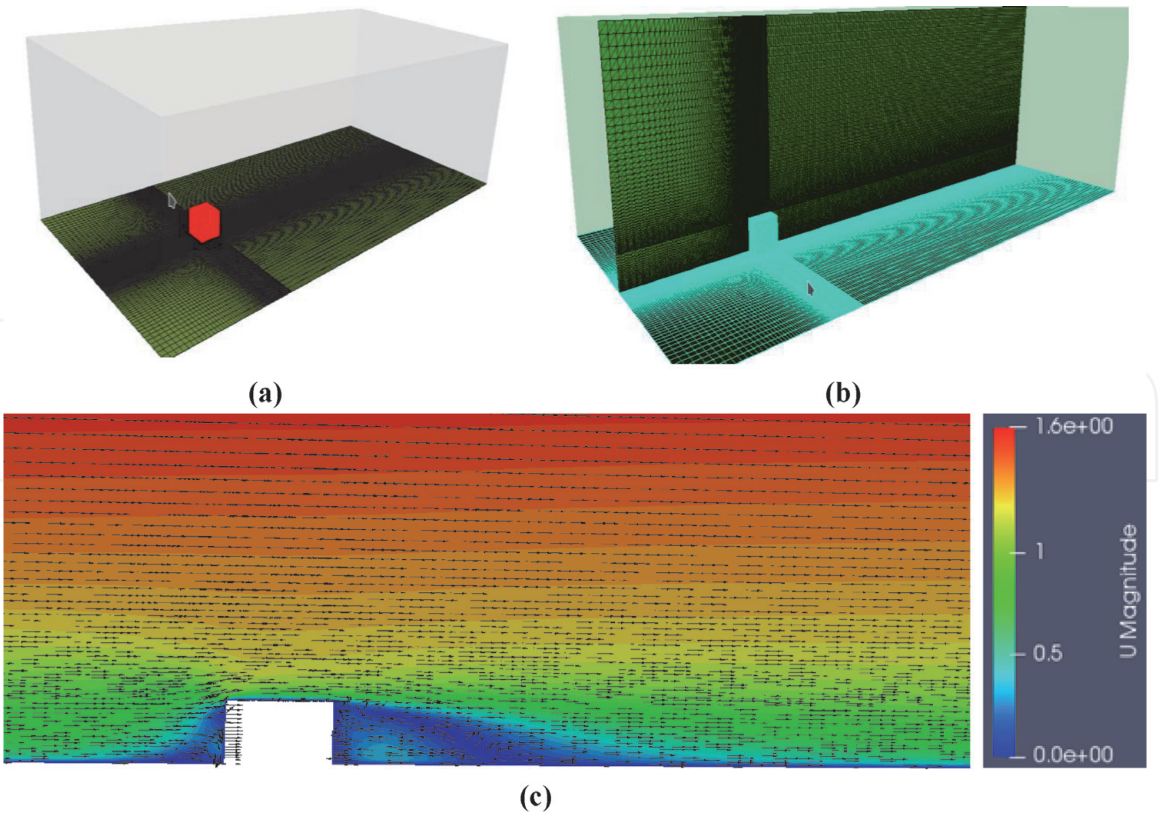


Figure 13.
With high-quality mesh and potential turbulence closure, CFD can provide continuous flow information: (a) 3D view of the computational grid, (b) meshing arrangement along the longitudinal section over a cube, and (c) velocity contour, after simulations in OpenFOAM.

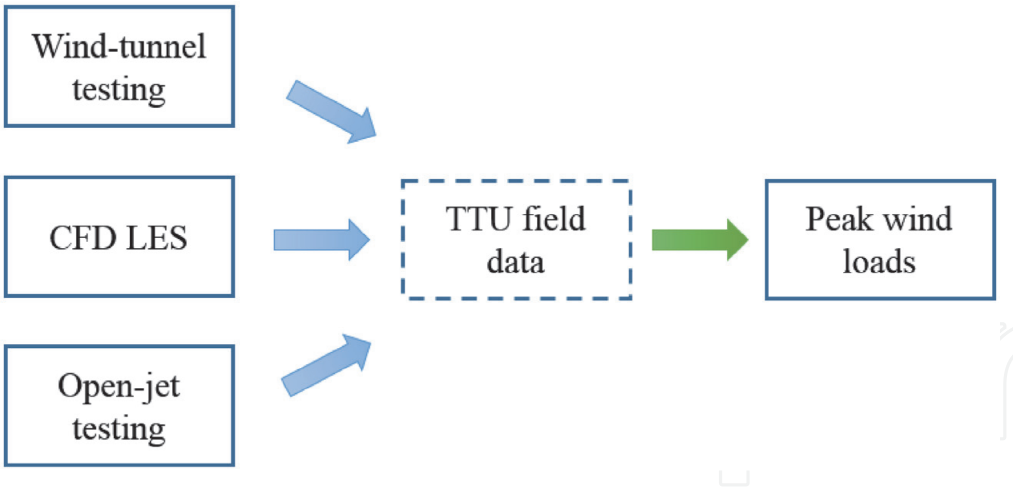


Figure 14.
The research tools employed to reproduce peak wind pressures on the roof of a benchmark low-rise building from the Texas Tech University (TTU) in an open-terrain field.

The CFD LES turbulence closure showed its capabilities to reproduce peak loads that can mimic field data owing to the ability of creating inflow with enhanced spectral contents at 1:1 scale [49].

7. Concluding remarks

This chapter described the main characteristics of ABL winds, as well as some available tools for aerodynamic testing. Earlier studies confirm the presence of extreme negative pressures near ridges, corners, and leading edges of roofs in wind events. Turbulence (small- and large-scale) is responsible for large peak negative pressures and separation in the shear layer. This demands for precise replication of wind speed profile, turbulence intensity profiles, and spectral characteristics. Replication of true physics requires equality of Reynolds number which is not possible in wind tunnels. In traditional wind tunnels, only small-scale turbulence can be generated. An increase in large-scale turbulence content in incident flow allows vortices to attain maturity, and as a result higher peak pressures are obtained. The challenge of properly simulating wind effects on low-rise buildings is related to the lack of capability in turbulence modeling at a reasonably large scale and its limitation in reproducing the low-frequency part of the ABL turbulence spectrum. As a result, advances in aerodynamic testing employing modern tools such as open-jet testing for large- and full-scale testing were devised in recent years. Resolving the scaling issue by studying larger models at higher Reynolds number is another highlight of recent advances in aerodynamic testing. A large-scale cubic building model was tested in LSU open-jet facility at higher Reynolds number, and pressure coefficients were compared with those from wind tunnel testing. The results reveal the importance of large-scale testing at higher Reynolds numbers to obtain realistic peak pressures. Furthermore, CFD with appropriate turbulence closure was widely implemented recently for full-scale studies of wind effects on civil engineering structures. However, adopting proper inlet transient velocity is very crucial to correctly simulate ABL wind characteristics.

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