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Towards Codification of Localised Windstorms: Progress and Challenges

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Abstract

Localised windstorms are a hazard for buildings and infrastructure in many parts of the world. Research has shown that they generate design-level wind gusts in many of these areas. Despite this, they are not explicitly considered in most wind-resistant design codes. The author suggests that this is because there is still a great deal we do not know about the characteristics of localised windstorms and their structural load effects, but argues that enough is known to begin the process of explicit codification. This paper provides an overview of existing wind engineering research investigating localised outflow-dominant windstorms and their loading of structures. It also details progress made by two wind-resistant design Standards that incorporate explicit design procedures for these events. Challenges for more widespread adoption of such explicit design procedures are discussed.

Introduction

Severe localised windstorms such as thunderstorm downdrafts and tornadoes cause widespread damage and loss every year. While thunderstorms are common in most parts of the world, it is primarily in the mid-latitudes, and away from coastlines prone to tropical cyclones, that they are of most concern to wind-resistant design. Tornadoes are the most devastating type of localised windstorm [27], but the probability that one will impact an individual structure is generally too low to warrant consideration in the structural design of typical structures [17]. This is not true for all types of structures and high-value or critical assets, such as nuclear power stations, may incorporate enhanced tornado-resistant design rules [48]. However, their low site-specific probability of occurrence means structures are not explicitly designed to resist them in most parts of the world. As such, and with a view to reviewing progress and challenges for general codification of localised windstorms, this paper does not consider tornado-resistant design. Instead, it focuses solely on the more common outflow-type localised wind events.

Over the last couple of decades wind engineering literature has generically referred to these localised wind events as 'downbursts' [e.g., 3, 37]. The name originated with T.T. Fujita, who used it to describe the family of localised, divergent windstorms, generally originating from thunderstorms [10]. The fact that there is not one type of 'downburst' is often forgotten. For example, in his pioneering work on the topic, Fujita [10] classifies two primary types of downbursts, the *macroburst* and *microburst*, differentiating the two based on the horizontal extent of damaging winds – the former being < 4 km and the latter > 4 km. Further classifying microbursts, Fujita explains that they can be; wet or dry, stationary or travelling, radial or twisted, midair or surface, outflow or rotor dominant, and can even contain cyclonic flow within their downdrafts. The flow kinematics within these sub-classifications are similar, but they differ enough to suggest that their surface outflows (which are of most interest to wind engineers) may not be the same. It is this event-to-event variability that has been a major hurdle for describing not only the structure of surface outflows from downburst events, but also the ensuing structural loading profiles required for codification.

There are four primary objectives of this paper. 1) To briefly outline existing research that has sought to quantify the structure of downburst-driven surface outflow wind fields and the loads they apply to simple structures; 2) based on these studies, present the case for why localised windstorms should be explicitly accounted for in wind-resistant design; 3) detail progress made towards codification of these events, and 4) discuss some of the major challenges faced when trying to do this. Here, we will only focus on the scientific and engineering challenges rather than political challenges that must also be overcome when updating or implementing design codes.

Background

Wind Field Characterisation

Wind engineers have undertaken dedicated studies of localised windstorms since the 1990s. The atmospheric sciences community have been studying them for much longer. Summarising this early work, [27] describes the distinguishing differences between localised outflow wind events and large-scale synoptic wind systems – which form the basis of all wind loading codes – as follows:

- Outflows are highly non-stationary,
- They are complex three-dimensional flows,
- Velocity profile with height do not follow 'traditional' boundary layer shapes, and
- Turbulence is lower and correlation higher in outflows than in synoptic wind systems.

Much of this knowledge was drawn from observational field campaigns in the USA [e.g., 15, 63], laboratory experiments with impinging jets [e.g., 3, 16] and early numerical studies [e.g., 45, 46, 49, 50]. Researchers have since extended these experimental [e.g., 22, 25, 37, 54] and numerical [e.g., 23, 41, 44, 61] studies to analyse some of the more transient features of these outflows. Fewer observational studies have been carried out [12, 19, 47], but where these data are available they provide great insight into not only the characteristics of outflows, but also the significant variability that exists amongst this family of events.

The conceptual picture of an outflow-driven windstorm is that of a descending jet of air (downdraft) that diverged radially after impinging on the ground. Divergence is forced by a region of high pressure (meso-high) located below the downdraft that accelerates winds as they are reoriented parallel to the surface (Figure 1). Early observational studies identified the existence of a ring vortex at the leading edge of the outflow [10, 15, 63]. A phenomenon also observed in laboratory experiments when a volume of dense liquid was released into quiescent fluid [1, 33] – a process qualitatively similar to the descent of cold (more dense) air in the atmosphere. Unfortunately, the small scale of these experiments and the complexity and expense of field studies meant that early wind engineering studies primarily focused on the analysis of wind fields produced by steady flow impinging jets [e.g., 16, 64] a model that numerous authors had qualitatively and quantitatively compared favourably with outflow observations [10, 15].

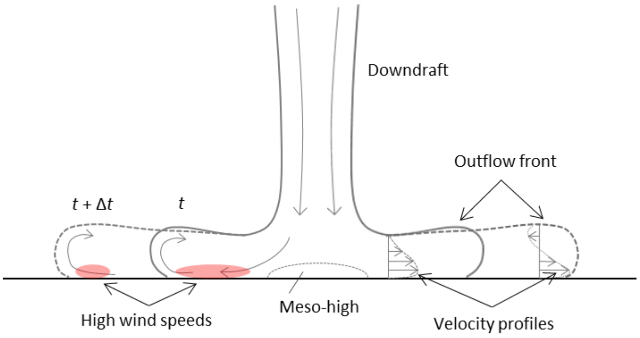

Figure 1. Schematic diagram of section through conceptual model of downdraft outflow event showing the regions of high wind speed, progression of outflow front with time (time t and $t + \Delta t$), meso-high below downdraft, and approximate velocity profiles in the impingement and diverging front regions.

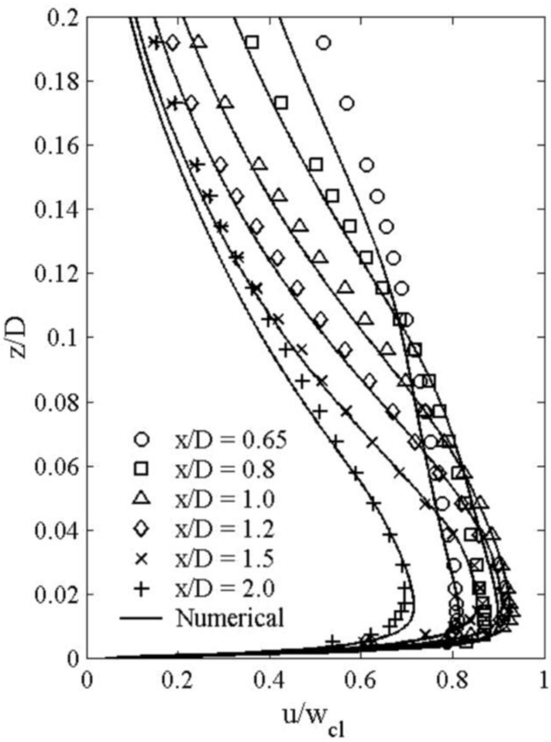

Figure 2. Experimentally and numerical velocity profiles at various radial distances, x/D, from the centreline of a normally impinging jet [40]. D is the diameter of the jet, u is wind speed parallel to the impingement surface, w_{cl} is the jet velocity and z is distance from the impingement surface.

While the use of a steady jet to simulate an unsteady process was a simplification, its use did allow some important features of downburst-like outflows to be understood. For instance, Figure 2 shows the wind speed profiles for flow parallel to the impingement surface at a range of normalised radial distances, x/D, from the centreline of a normally impinging jet (for scaling purposes the diameter of jet, D, is approximately 1-1.5 km in full scale). All profiles exhibit a 'nose' type shape, with a velocity maximum near the surface (approximately 15 – 30 m in full scale). Near to impingement (x/D = 0.65, 0.8) and very near to the surface, the velocity profile is relatively uniform with height. Further from the jet, the elevation of maximum velocity increases along with the depth of the divergent outflow. Accompanying this velocity profile change is a modification of the turbulence profile, and [40], along with others, show that turbulence kinetic energy increases by a factor of 2-3 between x/D = 0.8 and x/D = 1.5. This observation conforms with meteorological observations that suggest outflow winds exhibit relatively low levels of turbulence in their early stages [19]. Studying this further, [5, 40, 65] showed that velocity and turbulence profiles near the impingement location were insensitive to the underlying surface roughness. Further from the jet, however, peak velocity magnitudes at the profile 'nose' decreased and the elevation of that nose increased for rougher impingement surfaces. This intuitively makes sense when considering that the diverging surface outflow is in essence a developing boundary layer.

Extending these experiments to investigate how downburst-like outflows behave when moving over topographic features, [16, 26, 39, 64] all showed the amplification of winds to be 10-15% less than observed in traditional atmospheric boundary layer winds. They reason that this reduction in amplification is due to the non-confined nature of the diverging jet, which, unlike the ABL is able to adjust away from the surface as it moves over the topographic feature.

Acknowledging limitations of steady flow experiments, both experimental [25, 37, 54] and numerical [23] simulations with unsteady impinging jets have been undertaken. For example, Letchford and Chay [25], using a translating impinging jet showed that the physical structure of the leading edge gust front was modified by translation of the simulated downdraft. This highlighted that while steady jet tests did allow some aspects of the outflow to be studied, they were not able to emulate all aspects of the unsteady wind field. Letchford and Chay [25] also showed that it was within this leading edge gust front that the strongest wind reside. This echoed earlier numerical simulations using an idealised 'cooling source' model for both stationary and travelling microbursts [45, 46].

The focus of more recent experimental [14, 22, 37] and numerical [23, 54] impinging jet studies has been on impulsively started jets. In principle, these jets allow the leading edge gust front to be more faithfully produced. Figure 3 is an example of results from the Texas Tech pulsed jet simulator [37], where the velocity profiles at a range of radial distance (*X/D)* for both steady flow conditions (as in Figure 2) and within the diverging gust front are shown. Velocity magnitudes within the front are significantly greater than in the steady flow regime (the exact ratio differs depending on experimental setup). These profiles still exhibit peak wind speeds near the surface, which similarly reduce in magnitude and lift from the surface as X/D increases. Flow visualisations and numerical impinging jet simulations reveal that a distinct ring vortex develops at the leading edge of the outflow and the peak measured winds are generally located beneath its core. Again, these experiments showed the importance of considering the transient nature of these events.

Research with impulsively started jets continues in a number of laboratories around the world, with the large scale facilities at both the University of Birmingham and Western University being particularly active. Numerically though, a recent trend has been towards the use of more thermodynamically complete simulations. In these, downdrafts are either driven by idealised energy sinks (cooling sources models) [e.g., 41, 61] or by fully resolving thermodynamic processes in cloud models [44]. These simulations generate outflows qualitatively similar to those produced by impinging jet studies. However, they do much better – particularly the cloud model – at simulating the spatial variability within these events. For this reason, the author believes this type of simulation will be a vital tool for improving our understanding of outflow events.

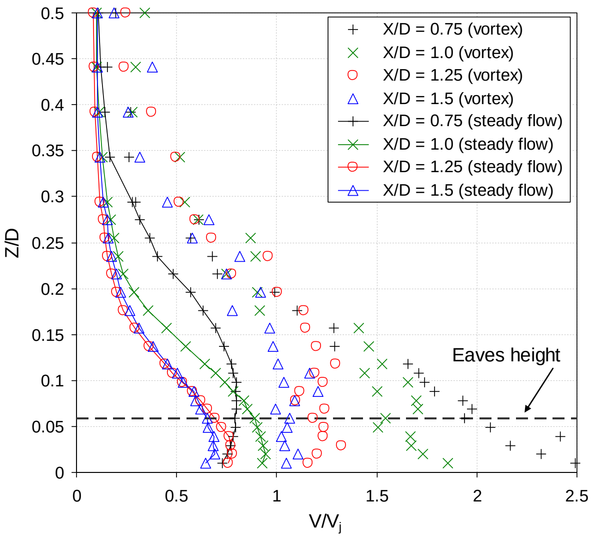

Figure 3. Normalised mean steady flow imping jet radial velocity profiles and averaged peak velocity profiles during the passage of a diverging ring vortex (based on [37]). In this figure, V is the velocity parallel to the impingement surface, V_j is the jet velocity, Z is distance from impingement surface and D is the jet diameter. Vortex velocities are the average of 10 repeat tests.

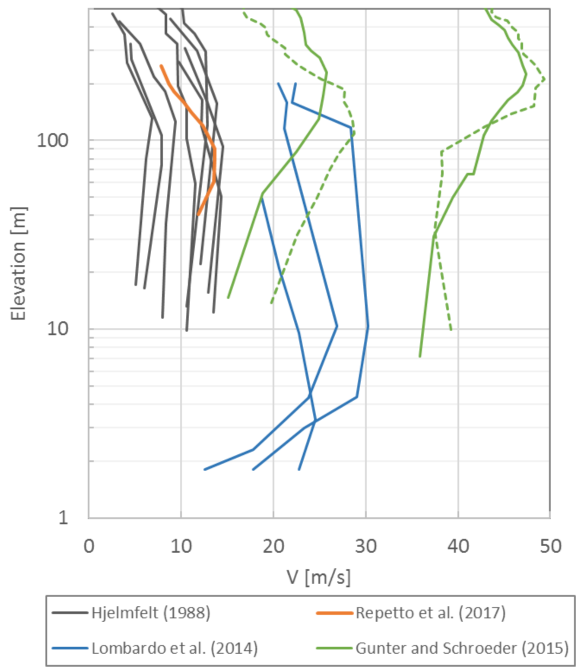

Figure 4. Measured instantaneous horizontal velocity profiles at the time of maximum intensity during outflow events. Hjelmfelt [15] Doppler radar measurements were in Colorado during the JAWS campaign, Lombardo et al. [32] (3-second gusts) at the Texas Tech WERFL instrumented tower, Gunter and Schroeder [12] in Kansas and Texas using Ka-band radar (dashed line is instantaneous velocity, solid line is 1-minute mean), and Repetto et al. [51] (10-minute means) in Italy using LIDAR. Note that wind speeds in Hjelmfelt [15] are maximum divergence values. They have been divided by 2 here on the assumption that the outflow is symmetric.

As shown, the vast majority of work undertaken by the wind engineering community has been either laboratory experimentation or numerical simulation. Much less has been done observationally. Some notable exceptions to this are recent works by Orwig and Schroeder [47], Lombardo et al. [32], Gunter and Schroeder [12] and Repetto et al. [51], where surface based towers, mobile Doppler radar or scanning LIDAR systems were used to measure outflow events. Figure 4 shows a composite plot of vertical profiles measured by those authors as well as the early Doppler-derived velocities from the JAWS campaign [15, 63]. While differences between acquisition and averaging times mean the wind speed magnitudes shown are not directly comparable, profile shapes are. All profiles display a low-level wind maxima, as shown in experiments, but the elevation of that peak varies considerably. For example, in the three tower-based measurements reported by Lombardo et al. [32] the maxima is at or below 10 m. Radar- based profiles by Hjelmfelt [15] and Gunter and Schroeder [12] report maxima between 60 m and 200 m, and Repetto et al. [51], using a LIDAR system, shows the maxima at approximately 80 m. From this limited number of observations, it is clear that variability between events is significant and cannot be fully explained using generic impinging jet (steady or unsteady) models. In the future, more focus will need to be placed on measuring outflow events so these complexities can be understood in detail.

Design Wind Speeds

It is evident that localised windstorms are different physical phenomena to large-scale synoptic wind events. They require different atmospheric conditions to occur and impact much different (smaller) physical areas. They do not occur with the same frequency or intensity and, as highlighted in the previous section, display very different physical characteristics. Even within the category of localised windstorms, there is evidence that outflows triggered by different mechanisms, e.g. surface heating or fronts, occur at different rates and with differing intensities [9, 56]. As such, when assigning exceedance probabilities to wind speeds at a given site (or even within a region), localised and synoptic wind events should be treated separately.

Gomes and Vickery [11] showed for a number of locations around Australia that when analysing sites exposed to mixed wind climates (i.e. exposed to a mix of tropical cyclone, synoptic and/or thunderstorm wind gusts) more accurate probability estimates were achieved by splitting wind records by their meteorological origin. Once this was done statistical distributions were fit to each record and then combining into composite diagrams. When plot in log-linear space, bi-linear Gumbel exceedance probability curves were found, with different meteorlogical phenomena often defining the combined low- and high-probability ranges. Comparing composite estimates with those derived from similar statistical analyses of the full (non-separated) record showed that not splitting records into their constituent meteorological origins generally led to unconservative gust estimates, particularly at low probabilities (i.e. long return periods) of interest to wind-resistant design.

Numerous researchers have since applied similar split wind climate analyses to wind records around the world [e.g., 6, 7, 18]. Each adopts different statistical techniques, but all show the importance of separating and analysing winds based on their meteorological origin. The necessity for doing this is now well accepted and forms the basis for design wind speeds in codes and standards [e.g., 18], and is common practice in consulting wind engineering when defining design wind speeds for specialist structures. Further to this, split wind climate analyses also allows the estimation of wind speed probabilities for each type of wind event present at a site. That is, not just identifying what wind speed has a given exceedance probability at a site, but what the wind speeds are at that site for each meteorological origin. This is an important outcome of these analyses and is required when developing explicit design procedures for localised windstorms.

Wind loading of structures

In his pioneering wind tunnel experiment at The Technical University of Denmark in the 1950s, Jenson showed the importance of both turbulence and velocity profile (which are intricately linked in a steady boundary layer) in defining the pressure distribution around a model building [17]. These experiments were the basis for much of the boundary layer wind tunnel experiments that have occurred since, and are the basis of wind-resistant design codes around the world. They, and many subsequent tests [e.g., 52], showed that the size and intensity of the separation bubble at the leading edge of the roof is significantly modulated by the level of turbulence in the oncoming flow. This modulation meant that reattachment points and wake dynamics were also altered and subsequently the pressure distribution over the entire building.

With this in mind, the following questions are posed for localised windstorms.

1. Will the difference between outflow and standard ABL velocity and turbulence profiles lead to different pressure loads on structures?
2. Given the transient nature of outflow events, will the rapid changes in wind speed, wind direction, ambient pressure and velocity/turbulence profiles alter building aerodynamics?

Both of these must be addressed.

On the first question,[3] studied the pressure distribution on a cube submerged in stationary impinging jet flow. The cube was positioned at a range of distances from the jet, and pressures over the centreline were analysed and compared with pressures on similarly dimensioned cubes in uniform and standard ABL wind fields. Near to the jet, where velocity profiles were relatively uniform and turbulence low, a distribution similar to that measured in uniform flow was observed. As the cube was progressively moved away from the jet, and wind profiles (velocity and turbulence) over the cube began to take on more traditional boundary layer characteristics, pressure distributions also began to look more like those in a traditional boundary layer wind field. To some degree, these results allow the first question to be answered. The shape of wind profiles (velocity and turbulence) do influence pressure loads on model buildings. Tests on different building shapes [e.g., 28, 66, 67] and for different jet inclination angles [38] concluded similarly. However, despite this conclusion, no systematic rules for how the profile shape and tubulence levels influence surface pressures have been developed. This remains an open challenge.

Noting the limitations of simulating a non-stationary phenomena with a steady impinging jet, researchers utilised transient [25] and impulsively-started [e.g., 21, 22, 36] impinging jets to study transient loads on a range of different building shapes. While the unsteady nature of these results made analysis, scaling and normalisation difficult, results again allude to differences when compared with ABL wind loads. In further analysis of these results, [25] also show that because the physical structure of transient outflows differ from steady impinging jets, quasi-steady models may be inadequate for estimating transient load effects. Recently though, [24] had greater success applying a quasi-steady model that incorporated both vertical and incidence wind angles as variables when estimating wind loading during a simulated tornado. While their model did show some deficiencies, it may be a promising path forward for estimating transient loads during outflow events. Further research on this topic is required.

An important point of difference between ABL and outflow wind loading is the importance of the high-pressure region beneath the downdraft (i.e. meso-high indicated in Figure 1) [25, 36, 53]. In typical wind load calculations the atmospheric (static) pressure is assumed constant in space and time. Therefore, all pressure loads on a body are governed by flow kinematics. For downdraft-type events though, the positive pressures beneath the downdraft can markedly influence measured loads within this region. These influences can be on the order of the maximum dynamic wind pressure and if not equilibrated across building surfaces, could present an issue for some structures.

While the discussed non-stationary experiments serve to highlight the fact that differences exist, they do not adequately address *why* they exist. In particular, it still remains unclear whether differences are simply due to different oncoming wind profiles, or if the transient nature of loading in some way alters the aerodynamics. This question remains largely unanswered, but fundamental work addressing the latter of these is now underway [e.g., 2, 55, 59]. These studies have shown that if acceleration rates are high enough in the wind field, considerable increases in both along- and cross-wind loading can occur. For example, [59] found that peak cross-wind forces on an elliptic cylinder during periods of rapid flow acceleration could be as great as 7 times higher than forces measured in steady flow. Extending this to a low-rise building, [60] similarly showed amplification factors on the order of 5 times greater than for steady flow at a number of pressure taps within the flow separation region of several roof shapes.

These results are initially alarming, and would suggest major structural failures - even at wind speeds well below design levels - should be common. Fortunately, this is not the case. Through use of the Morison Equation, commonly used in oscillatory hydrodynamic studies, it can be reasoned that the along-wind drag force should be dependent on a non-dimensional number of the form $LC_M \frac{dV}{dt}/C_D V^2$($L$ is a characteristic length, C_M is the so-called added mass coefficient, C_D is the drag coefficient, t is time and V is the wind velocity). This suggests that amplification of drag loading during accelerating flow is proportional to flow acceleration, but inversely proportional to the flow velocity squared. As such, tests at low wind speeds (as many wind tunnel tests are) may lead to higher amplification of loading than would be expected at full-scale and at design wind speeds. Several of the studies by Takeuchi and colleagues, show this to be the case.

Using velocity and acceleration time histories from a single outflow event (Andrews Airforce Base Microburst), [43] reasoned that for a generic structure with a characteristic dimension of O 6 m, amplification of only a few percent should exist at design wind speeds. This finding is predicated on a suite of assumptions, but does at least put the earlier load amplifications in context. This said, a great deal more work is required to fully understand the role of flow transience (acceleration and deceleration) on a range of different structure types and over a range of scales (note that as L increases, so too does amplification).

The Case for Codification

The previous section has shown that wind profiles (velocity and turbulence) generated during localised windstorms differ from the standard ABL assumed by codes and standards for wind-resistant design. It also showed that the result of this was differing load patterns on structures when exposed to these winds. Given this, the question must be asked, are we designing structures inappropriately?

The short answer is probably, yes, but it is unclear whether the quantum of difference is substantial enough to elicit change. In light of current knowledge, if wind-resistant codes were being drawn up for the first time, it may reasonably be expected that localised windstorms (outflows and tornadoes) – given their transience and vastly different spatial scales – may, from the outset, have their own design procedures. However, given current practice is strongly reliant on the assumption of a steady boundary layer, some argument must be put forward to convince people that change is needed.

There are two primary arguments that could be used. The first is safety. Does neglecting explicit design for these events make a structure unsafe. The second is cost. Does not explicitly designing for outflow events make a structure unnecessarily costly. The first is the route engineers often take, but it may be the second that is more appropriate here.

Through use of an Available Dynamic Pressure Ratio (ADPR), [35] put forward a simple method for comparing total along-wind loads on a hypothetical buildings exposed to traditional boundary layer and simulated downburst-like flow. They showed that using an ABL profile rather than an explicit downburst profile was a conservative design approach for buildings greater than 10-20 m high (assuming their numerical profiles are representative of design events). Below this, they suggest it may not be conservative, but caution that some of the assumptions made in their numerical model may bias this finding. Applying the same analysis to the range of observed JAWS microburst profiles, the authors also showed that for all except one profile, use of an ABL would be conservative for taller structures. When aggregating both numerical and observational data, the authors highlight that for a 200 m tall structure, overall along-wind downburst loading is between 5-75% less than ABL winds with an equivalent wind speed at 10 m height.

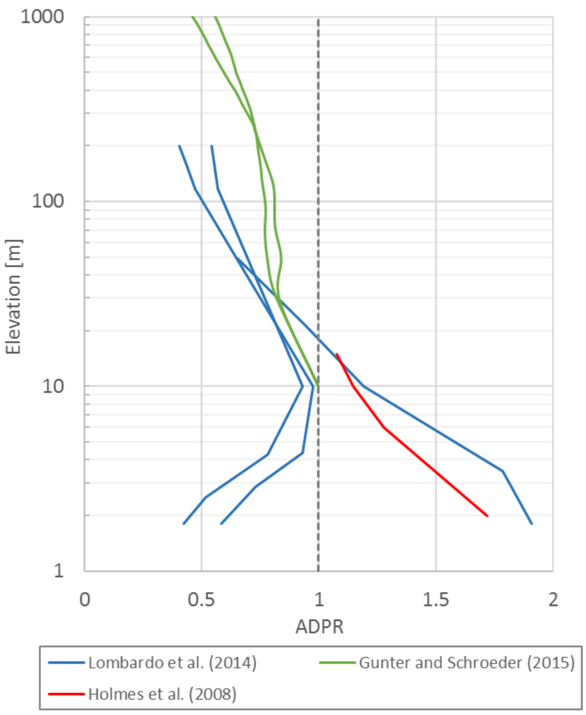

Figure 5. Available Dynamic Pressure Ratio (ADPR) calculated for enveloped full-scale outflow data when referenced to a logarithmic ABL profile with z_0 = 0.02 m and velocities matched at an elevation of 10 m. The grey dashed line indicates ADPR = 1.

Figure 5 shows the same ADPR analysis applied to the observed profiles reported in Lombardo et al. [32], Holmes et al. [19] and Gunter and Schroeder [12], discussed previously. Enveloped outflow wind speed profiles (shown in Figure 6) are compared with logarithmic boundary layer profiles (z_0 = 0.02 m) and wind speeds are matched at an elevation of 10 m. This figure shows qualitatively similar results to those observed by [35]. Two profiles show that for structures less than 20 m the available pressure energy in the outflow events are greater (i.e. ADPR > 1.0) than what would be available in a typical boundary layer flow. Above 20 m, all profiles contain less energy than the assumed ABL and its application in a design setting would lead to conservatism. Again looking at an assumed building of 200 m height, Figure 5 suggests the integrated pressure energy is 25-50% less for outflows than for the assumed ABL profile.

Therefore, it appears that different arguments should be made for low- and high-rise structures. For low-rise buildings, exclusion of explicit design procedures may lead to unsafe design. For high-rise buildings, however, it appears that not explicitly designing for these events will mean design are unnecessarily costly. There are numerous assumptions that go into these conclusions, but the level of overdesign that may be occurring for tall and very-tall structures could be considerable.

Progress Towards Codification

To the author's knowledge, there are only two codes or standards that explicitly require, or provide detail that enables, design for localised downburst-like winds. These are ISO4354 (2009): Wind actions on structures [20] and AS/NZS7000 (2010): Overhead line design – Detailed procedure [57]. The first is an international standard used for design of a range of structures, but the latter is only for the design of overhead transmission lines in Australia. Other wind-resistant design standards in Australia do not explicitly design for these events.

ISO4354 (2009)

ISO4354 provides an enveloping profile of peak wind speeds for thunderstorm-generated outflows. It suggests that turbulence profiles during these events may differ from typical boundary layer conditions, but due to a lack of observational data, does not provide outflow specific turbulence intensities, spectra or correlations. No event-specific modification of aerodynamic shape factors (pressure coefficients) are provided. As such, if only a single reference velocity is used there is no translation of the non-ABL profile onto the structure. For structures over 25 m, however, (where elevation dependent design wind speeds are used) some external and internal shape factor calculations will differ for thunderstorm profiles.

When calculating design wind speeds, ISO4354 requires a split wind climate analysis if the site of interest has a mixed wind climate. It discusses the example of having different profiles for ultimate limit (low probability of exceedance, i.e. safety) and serviceability limit calculations. This alludes to the need to determine at what probability of exceedance each event type becomes 'dominant'.

Figure 6 shows the profile shape of the ISO4354 envelope profile and compares it with envelope profiles for the data measured by Lombardo et al. [32], Holmes et al. [19] and Gunter and Schroeder [12]. The first two of these are as previously introduced, and Holmes et al. (2008) is anemometer data from the Lubbock-Reece rear-flank downdraft (2002). All data are normalised by their wind speed at 10 m elevation. The ISO4354 profile is conservative below an elevation of 10 m based on both the measurements at WERFL and those discussed by [19]. Above this height, ISO4354 reasonably approximates Holmes data, is conservative with respect to Lombardo, and is a reasonable estimate of one of the Gunter and Schroeder profiles. It underestimates the other above 100 m.

AS/NZS7000 (2010)

AS/NZS7000 provides a framework for the design of overhead power lines in Australia and New Zealand. This standard is based on the Australia/New Zealand wind loading standard, AS/NZS1170.2 [58], but deviates from it in that it provides distinct design requirements based on windstorm type (synoptic or localised). Specifically, AS/NZS7000 provides:

- Regional storm type map showing where localised downdrafts must be considered,
- Storm specific design wind speeds,
- Downdraft wind speed profile,
- Topographic multipliers for use with the downdraft wind profile,
- Span reduction factors for both downdraft and synoptic wind events.

The regional storm type map has three zones. In Zone 1 design is for synoptic wind events only. In Zone 2, localised downdrafts only and in Zone 3 both must be considered. This type of zoning is similar to what is currently done in the Australia/New Zealand (and others) standard for identifying areas prone to tropical cyclones. It is also an essential first step in the codification process as it identifies where localised downdrafts are important and where they can be ignored.

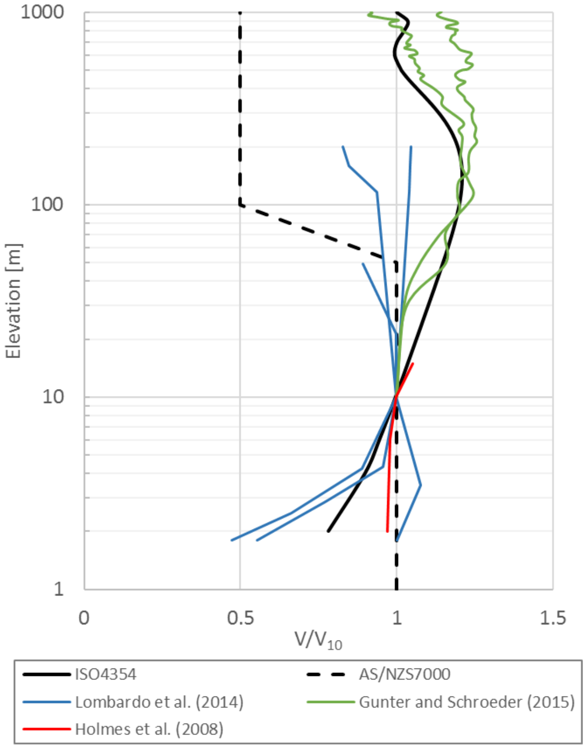

Figure 6. Envelope wind speed profiles from ISO4354 [20] and AS/NZS7000 [57], as well as, envelope profiles from full-scale outflow measurements described in Lombardo et al. [32], Gunter and Schroeder [12] and Holmes et al. [19].

The wind speed profile provided in AS/NZS7000 is simpler than in ISO4354. It is a vertical profile below 50 m that linearly decreases to 50% of the design wind speed at 100 m, then remains constant above there. This profile is shown alongside ISO4354 and full-scale observations in Figure 6. It is more conservative than ISO4354 below 10 m and reasonably matches observations up to 20-50 m. Above this, the AS/NZS7000 profile underestimates observed full-scale profiles. No storm-specific turbulence intensity or aerodynamic shape factors are provided, and there is no consideration of underlying roughness when defining the wind speed profile.

In addition to providing a downdraft wind speed profile, AS/NZS7000 also provides specific topographic amplification factors for use in these zones. Factor are variable dependent on slope, but are up to 20% less than those used for ABL flow. Based on steady and unsteady simulation results discussed earlier [39, 42], this order of reduction is reasonable.

AS/NZS7000 assumes thunderstorm downdrafts are uniform across the country. It does this by assigning the same design wind speed for downdraft design, but specifies use of the regional wind speeds provided in AS/NZS1170.2 for synoptic wind events. This leads to coastal areas being designed for higher synoptic wind speeds than downdraft wind speeds.

Finally, AS/NZS7000 provides storm-specific span reduction factors. While these factors are specific to overhead line design, what they actually consider is lateral correlations of wind gusts. Less reduction in load is specified for downdraft windstorms to account for the greater lateral correlation of loading during these events [19].

While AS/NZS7000 presents a relatively simplified method for considering localised windstorms in the design process, it does provide an example for how it can be done. Some of the challenges around making this process more accurate and streamlined are discussed in the following section.

Challenges

A major barrier to more rapid incorporation of explicit design for localised windstorms in design practice is our still incomplete understanding of both the phenomenon and its load effects on structures. This section will outline - as the author sees it - some of the key challenges to be overcome before widespread codification of these events can occur.

Wind Field Characterisation

Experimental and numerical simulation studies should continue to systematically explore specific features of localised windstorms. However, if the wind engineering community is to gain a greater appreciation of the true characteristics of these events, more observational research is required. There are signs that this is now occurring [e.g., 12, 51], but it will take a dedicated push to gather enough data to build a statistically sound model of these events. In particular, greater emphasis has to be placed on understanding the spectrum of localised windstorms so we can go beyond the idea that all outflows look like microbursts in Colorado.

While field measurements are time consuming and expensive, recent developments in remote sensing wind capabilities (i.e., mobile Doppler radar and LIDAR systems) will mean high-resolution spatial measurement systems can be deployed to events rather than waiting for these to occur near stationary instrumented towers. Challenges around spatio-temporal averaging makes integration with existing point measurement data complicated [13], but not insurmountable. Close collaboration with atmospheric scientists will also be required so that wind engineering objectives can be engrained into project design rather than wind engineers simply being an end-user of data gathered by others.

As suggested, there is certainly scope for more experimental and numerical simulation research to complement greater observational data. For instance, we still know relatively little about what outflow events that deviate from the simplified conceptual model of a stationary round jet of air normally impinging on a surface look like. Fujita [10] and Wakimoto [62] detail a range of different localised windstorms and it is incumbent upon us to understand them all. Many of these are morphologically different to the simple impinging jet so will exhibit different vertical and horizontal wind speed, turbulence and correlation profiles. In the author's view, building a greater understanding of the structure within rear flank downdrafts and downdrafts embedded in fast moving fronts are of particular importance.

Design Wind Speeds

One of the first tasks that must be undertaken before codification of localised windstorms is possible is to determine where they are of design interest. To do this split wind climate analyses must be undertaken and maps of relative importance developed. A practical difficulty for achieving this, however, is that information on meteorological origin of individual wind records is not always archived. This is particularly an issue for older records away from international airports. Even if classification is included, it may not be internationally (or even nationally) consistent. In such cases, other meteorological data, including wind direction, radar scans, rainfall, temperature or pressure records can been used to automate origin classification [e.g., 8, 30].

For many parts of the world, split wind climate analyses are possible with current weather station networks. However, given the small spatio-temporal scale of localised windstorms there will be areas not adequately sampled. For these areas, solutions such as statistical inference [e.g., 4] or event-based stochastic modelling [34] that incorporate large scale global reanalysis data sets, may offer a means by which these areas can be understood. Development of such statistical models will also aid our ability to estimate windstorm risk in future climates.

Going forward, the global trend towards greater coverage of weather sensing instruments (weather stations, radar, satellite) will offer new opportunities for automated detection and attribution of storm types to extreme gust measurements. Wind engineers must stay on top of these developments and use them to facilitate split wind climate analyses. Use of these tools to even sub-categorise localised storm types, such as done by [56], should be explored.

Wind loading of structures

Recent construction of large-scale non-traditional wind tunnel facilities, e.g. WindEEE [14], offer significant opportunity for understanding the load effects of localised windstorms. Unlike for flow field characterisation, where scale is not essential – and in many instance makes testing considerably more complicated – when assessing loading of structures testing at scales approaching that used in other wind tunnel tests (i.e. *O* 1:400) is desirable. This scale also allows turbulence to be modelled appropriately. However, it is important that these facilities do not further engrain the notion that there is only one type of outflow event. Flexibility of test setup, such that downdraft shape, translation speed, incidence angle and existence of ambient environmental wind conditions can be modified to reflect an evolving observation-derived understanding of what localised outflows are, will ensure the value of these facilities.

An alternative approach is partial boundary layer simulation. In essence this is what traditional boundary layer wind tunnel testing is, so there is certainly merit in pursuing this option. It involves simulating part of the outflow, which then facilitates testing of structures at a range of scales. However, because the transient three-dimensional characteristics of a true outflow are not modelled, this information must be drawn from observations, numerical simulations or other laboratory experiments. The advantage, however, is that if done correctly the cost and space requirements are significantly less than those of a modern large-scale test facility. Following this reasoning, [29] used a wall jet within a traditional boundary layer wind tunnel to simulate a two-dimensional outflow front. More recently, a number of multi-fan wind tunnels have been developed (e.g. Tongji University (China), Tamkang University (Taiwan)), which follow on from the successful application of the Miyazaki University (Japan) multi-fan wind tunnel for this purpose [e.g., 2]. Given the ability of these facilities to independently control spatio-temporal wind speed and turbulence characteristics, this author believes they have a significant role to play in furthering our understanding of wind loading during localised windstorms. One drawback, however, is that while flow kinematics can be reproduced (although not without difficulties), static pressure fields associated with these windstorms cannot. How significant this is, is still unclear.

While both large-scale and partial boundary layer simulation methods offer a means by which transient, non-ABL boundary layer winds can be applied to model structures, they still apply wind fields with strong coupled spatio-temporal velocity (and possibly pressure) gradients to a structure. The author strongly argues that a more fundamental approach is required if loading is to be understood rather than simply reproduced. To this end he suggests that a constituent approach of assessing, for example, flow transience, profile shape and profile transience, in isolation is required. The author and his collaborators, as well as several other researchers around the world, are currently undertaking research through this framework.

Much of the discussion to here has been around flow simulation methods. But, considerable challenges also exist on the analysis side. In particular, methods for analysing transient load effects (dynamic or quasi-steady) are only now emerging and will require time and effort to validate in an industry premised on the concept of a stationary boundary layer profile. This will be an interesting space to watch unfold over the coming years.

Finally, and reiterating the idea introduced earlier in this section, while wind tunnel and numerical testing are indispensable tools, considerable value is gained by full-scale observation. Studies of full-scale loading of real structures during localised wind storms, such as that detailed in Lombardo and Mason [31], will be invaluable for validating test methods and analysis procedures developed by researchers around the world.

Conclusions

This paper presented an overview of current understanding of outflow-type localised windstorms and their loading of structures. While much has been learned about flow field and loading characteristics through simplified engineering models, more full-scale observations are essential if wind engineers are to gain a full appreciation of the spectrum of outflows that exist and affect structures. Test facilities that allow these observations (or high-resolution numerical simulations) to inform test setup will be particularly useful for building an understanding of the complex transient load cases these events generate.

Globally, only two wind-resistant design codes currently incorporate explicit design for localised windstorms. Their procedures are relatively simple, but do pave the way for a more detailed framework to be developed. While research is still needed to fully understand how and why localised windstorms load structures differently to ABL winds, there is enough evidence to say that they do. As such, action towards incorporating explicit design procedures should commence. The first step in this process is to determine where (globally) localised windstorms are important. This can be done with current datasets and analysis methods. Provision of a generic vertical wind speed and turbulence profile should also be a priority. This would be of particular use to the design of tall and very tall buildings.

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