Title: **Tall Buildings, Operable Facades, Wind, Life Safety – Designing for the Risks**

Authors: Tom Neudorfl, Senior Consultant, Murchie Consulting
Ross Murchie, Director, Murchie Consulting

Subjects: Façade Design
Fire & Safety
MEP
Wind Engineering

Keywords: Façade
Life Safety
MEP
Residential
Risk
Wind

Publication Date: 2015

Original Publication: Global Interchanges: Resurgence of the Skyscraper City

Paper Type:

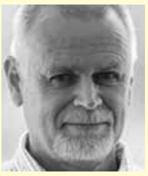
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Tall Buildings, Operable Facades, Wind, Life Safety – Designing for the Risks

Tom Neudorfl
Senior Consultant

Murchie Consulting,
Melbourne, Australia

Tom has a Bachelor of Applied Science in Mechanical Engineering from the University of British Columbia. He is passionate about the engineering of built environment dynamics that affect how people feel - acoustics, vibration, wind and natural ventilation. He has provided advice on tall buildings including Burj Khalifa, Princess, Elite, and Marina Crown in Dubai, Landmark Abu Dhabi, Tower Melbourne, Lighthouse, Collins House, Avant, and Empire Melbourne. In a past role, Tom managed a boundary layer wind tunnel and a facade lab, and despite currently focusing primarily on acoustics, wind effects on operable facades remain a key area of interest.



Ross Murchie
Director

Murchie Consulting,
Melbourne, Australia

Ross has over 25 years' experience in MEP design consultancy on projects throughout Australia and Asia. As director of Murchie Consulting, he leads Australian thinking and innovation in the engineering of tall residential buildings, exploring integrated and highly value-engineered solutions to the emerging technical and economic challenges that these buildings face. His experience spans mechanical engineering, energy, vertical transportation, management of engineering projects, and management of large engineering teams. He has successfully delivered hundreds of major projects from master planning through construction in Australia, Indonesia and the Philippines.

Abstract

2015 records an unprecedented number of tall and super-tall buildings completed worldwide. Furthermore, residential buildings with operable facades form an increasing proportion of these tall buildings. There is an immediate need to better understand the risks of wind effects on tall buildings with operable facades – risks to safe evacuation, operation of lifts in emergency situations, effective operation of mechanical smoke management systems, and risks to the integrity of internal walls and other internal elements.

These risks are presently not addressed in building codes, and they are typically underestimated in present standard design practice. Thus, it is imperative to either improve regulations or to redefine what is considered appropriate tall building design convention. In the meantime, designers must exercise their responsibility and judgment to ensure that designs remain fit-for-purpose under realistically occurring conditions. This paper explores a number of these risks, and proposes practical design approaches for mitigation.

Keywords: Façade, Life Safety, MEP, Residential, Risk, Wind

Tall Residential

The year 2015 records an unprecedented number of 200+ meter buildings under design in Melbourne and a steadily increasing number of tall and super-tall buildings completed worldwide. More and more of these new buildings are residential, featuring operable ventilating façades. Whereas a building with a sealed façade isolates the interior from wind pressures, these buildings behave differently: the operable façade allows wind pressures to transmit into the interior, where they can adversely affect the operation and integrity of internal components and systems.

Around the world, building codes and standards define design criteria with which architects and engineers must comply. The assumption is that these codes and standards reasonably address major safety concerns, and that compliance therefore ensures a minimum acceptable level of building safety. Sometimes, however, codes and standards do not evolve as quickly as design trends do: the risks of wind effects on tall buildings with operable facades are presently not addressed by Australian codes, nor by a range of other codes internationally. Australian experience shows that they are also typically underestimated in present standard design practice. There is thus an immediate need for a profoundly new approach to the design of these buildings to ensure long-term safety and serviceability. The hope is that this thinking will redefine what is seen as adequate design convention for tall residential buildings, and that ultimately this will inform the improvement of regulations.

A New Breed of Building

Historically, most high-rise buildings have been commercial office buildings. These typically have had a sealed façade, and they have been places for work – they served a relatively utilitarian function and their performance was judged on that basis. Tall and super-tall residential buildings with operable ventilating façades, however, are in effect a new breed of building – one in which perception of comfort, amenity, and personal connection to the space is a higher priority. Complaints are common. They include howling and creaking noises, wall and ceiling damage, vibrating and damaged door seals, poor ventilation and condensation, pressures that make the opening of doors difficult, lobby pressures that stop lifts from operating correctly, and damaged components of the façade.

Every building contains components and systems that are highly sensitive to pressure. For a sense of relative magnitude, Figure 1 plots the pressure differential limits for several internal

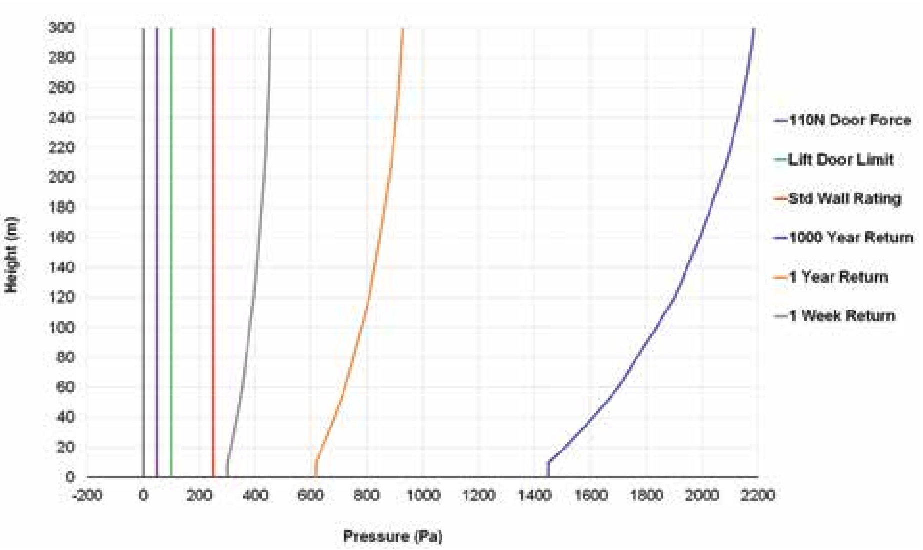


Figure 1. Comparison of internal pressure limits to peak gust wind pressures of varying return periods, showing the large difference in magnitude between internal requirements and external conditions (Source: Murchie Consulting)

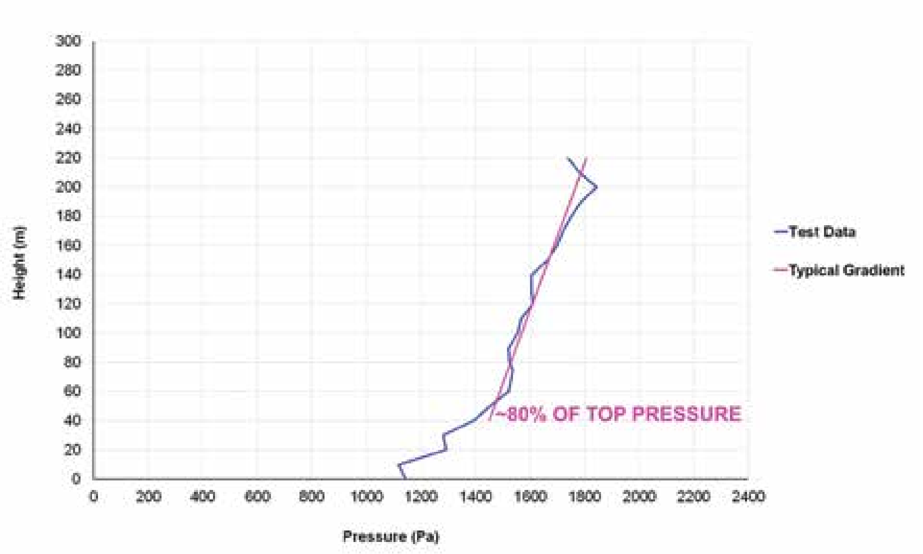


Figure 2. 1000-year return period peak gust windward positive cladding pressures for average of six 200+ m buildings in Melbourne, showing relatively high pressures even at the lower levels of the building (Source: Murchie Consulting)

building elements as well as external pressures occurring with varying return periods. The internal limits are low, and the external pressures can be very high – a risky situation when the façade is open.

Disruption of amenity is not the only thing that can go wrong. Wind pressures also present a risk to safe emergency evacuation of a building because they can affect the operation of the mechanical smoke control and other life safety systems. Although such failures occur relatively infrequently, this is in part due to the low frequency of major fires. Failure is less likely, but consequences are far more severe. The abundant anecdotal experience of poor amenity in tall residential buildings demonstrates that wind pressures are a real problem. It follows that wind must be considered in the responsible design of all potentially affected building systems.

Wind and Building Interaction

Wind speed increases with height above the ground, and it also fluctuates in time both as a result of changing climate conditions and, at a much higher frequency, as a result of turbulence in the urban boundary layer – wind gusts. The wind pressures on a building, in particular a tall building, vary accordingly, with positive pressures on the windward elevation, and negative pressures on the leeward and side elevations. These pressures also increase with height, with the mean component of wind speed resulting in a mean pressure and wind gusts resulting in pressure pulses. Figure 2 shows the variation with height of the 1000-year return period peak gust windward (positive) pressures for six 200+ m buildings currently under design or construction in Melbourne.

The data presented in Figure 2 demonstrates that relatively high pressures can occur even at the lower levels of a tall building. In this case, the data indicates that approximately 20% of the way up the building, pressures already reach approximately 80% of the maximum occurring near the top.

In addition to the positive windward pressure shown in Figure 2, buildings are also subject to negative pressures on the leeward elevation, and to a lesser extent on the along-wind elevations. These negative pressures are typically of even greater magnitude than the positive pressures, and they are typically even more equally distributed across the façade surface. Figure 3 illustrates an example of windward and leeward pressure distributions on a building of approximately 220 m high.

The implication is that at any given height above the ground, façade pressures on a taller building will be greater than they would be for a shorter building. Thus, wind pressures need to be considered over essentially the full height of a tall building. In Australia, there is a prevailing approach to the design of tall buildings which assumes that the bottom part of the building will behave like a shorter building would, and that wind effects are only of relevance on upper levels. This is patently incorrect; the building must be considered as a whole.

Internal Pressures

In a sealed building, the large pressure difference between the windward and leeward faces manifests principally at the façade. While (unavoidable) leakage results in mild net negative pressurization of the building with respect to atmospheric pressure, relatively little differential pressure occurs across internal building components. Some internal differential pressures occur at zones connected to the outdoors, for

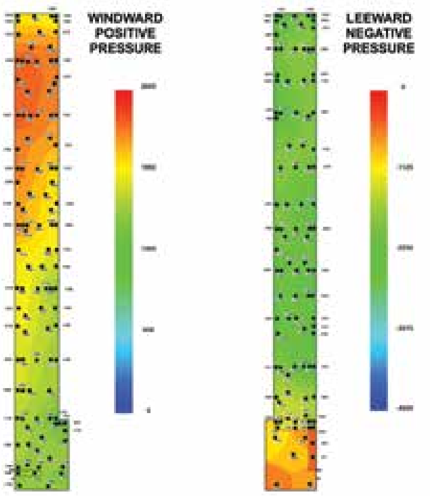


Figure 3. Example cladding pressure contours showing relatively high windward positive pressures even at lower levels and a uniform distribution of leeward negative pressures (Source: MEL Consultants)

instance shaft ventilation openings and mechanical system inlets and outlets, but such zones can be readily predicted and accounted for in the architectural and mechanical design.

On the other hand, openings in an operable façade, such as open windows or balcony doors, allow the wind pressures to transmit to the room within. An opening that transmits a substantial proportion of the pressure with little reduction is said to be a dominant opening. As the pressures are not necessarily accompanied by a flow, even windows and doors that are just cracked open a little can behave as dominant openings: they do not have to be open fully, a few millimeters is enough (Lamande, Xu & Bekele 2013). With the façade no longer providing isolation of the external pressures, the internal pressure equalizes to the external pressure, and suddenly the external pressures act against the partitions and building systems within the building interior.

The arbitrary location and distribution of façade openings at any given moment makes it very difficult to predict how the internal systems will be affected and presents a challenge to the design of mitigation measures. A couple of open windows in a single apartment might affect one or two internal walls, whereas a greater number of façade openings distributed across different faces and levels could result in large differential pressures throughout the building and flows through the building core that affect multiple building systems.

Building Elements at Risk

For a meaningful discussion of risk on a tall ventilated residential building, it is first necessary to identify individual detrimental wind effects. These can be categorized based on severity of consequence – ranging from severe life safety to minor loss of amenity – and the corresponding probability of failure that together determine a tolerable level of risk. Such a classification is shown in Table 1. Building elements 1-3 are equally relevant to any tall building, including those with a sealed façade; building elements 4-6 are of greater concern on buildings with an operable facade. The table also indicates if there exist agreed-upon design criteria to set a tolerable risk threshold.

	Building Element	Consequence	Tolerable Failure Frequency	Design Criterion
1	Structural Integrity	Severe	Very Low	Yes
2	Cladding Integrity	Severe	Very Low	Yes
3	Pedestrian Level Comfort	Moderate	Medium	Yes
4	Evacuation / Smoke Control Systems	Severe	Low	No
5	Internal Partition Integrity	Moderate	Medium	No*
6	Ventilation System Operation	Minor	High	No

Table 1. Categories of wind-related risks based on consequence and tolerable frequency of failure, showing an indication of those risks for which defined design criteria exist (Source: Murchie Consulting)

Absence of Agreed-Upon Design Criteria

As Table 1 shows, design criteria for wind-affected building elements relevant to tall buildings with sealed facades are well established. In Australia, for example, structures and facades are designed to the 1000-year return period peak gust (AS/NZS 1170.2:2011), and pedestrian level winds are assessed against comfort and safety criteria corresponding to the weekly and annual maximum peak gusts, respectively (Melbourne 1978).

Conversely, no such design criteria exist for internal effects, which are primarily a concern in buildings with operable façades. At best, codes and standards mention the need to consider wind effects, but they do not provide any numerical criteria. Figure 4 shows a prominent example.

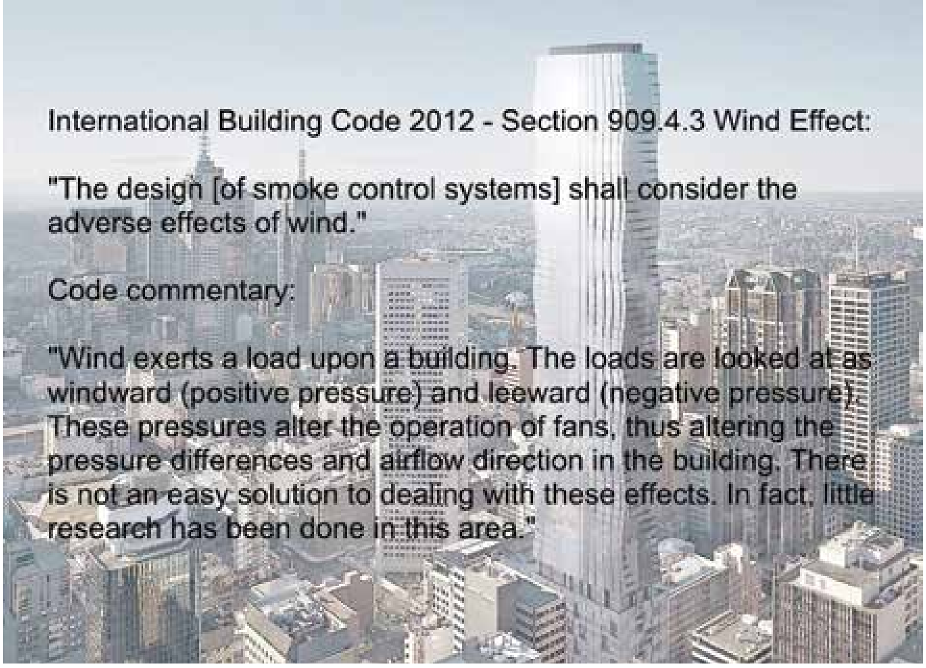
Similarly, from the UAE Fire and Life Safety Code of Practice (2011, p. 526) – Chapter 10, Clause 25.2:

> *The smoke zone exhaust shall discharge to the outside of the building. Design of the smoke zone exhaust system shall include an engineering analysis of the stack and wind effects.*

Even such code requirements, where they apply, beg the question. How should the wind be "considered"? What should the "engineering analysis" demonstrate?

Clearly, designing for code compliance alone is insufficient for a tall building. In Australia, additional analysis is not mandated by code or standards in any way, but even where regulatory requirements do exist, a suitable basis of design is missing.

On many development projects, the wind engineers provide wind tunnel test data only for the mandated structural aspects of the design, with results communicated to the structural and façade engineers. In the meantime, the mechanical engineers design the ventilation systems to overcome



International Building Code 2012 - Section 909.4.3 Wind Effect:

"The design [of smoke control systems] shall consider the adverse effects of wind."

Code commentary:

"Wind exerts a load upon a building. The loads are looked at as windward (positive pressure) and leeward (negative pressure). These pressures alter the operation of fans, thus altering the pressure differences and airflow direction in the building. There is not an easy solution to dealing with these effects. In fact, little research has been done in this area."

Figure 4. IBC 2012 Requirement for the consideration of wind effects on smoke control systems, along with the accompanying code commentary (Source: Elenberg Fraser Architects)

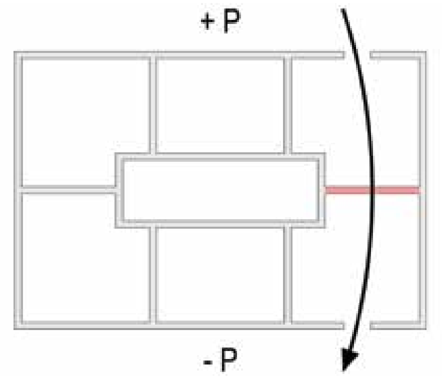


Figure 5. External pressures transmitted indoors and resulting in a differential pressure across an inter-tenancy partition (Source: Murchie Consulting)

system pressure losses, in accordance to relevant standards and guidelines. Given that system pressures are the essence of their work, the mechanical engineers are often best positioned on a project to also interpret and coordinate internal wind mitigation requirements. Unfortunately, they frequently lack a sufficient appreciation of the risks and the necessary understanding of wind engineering principles to do so. In short, there is a disconnection between who examines external wind pressures and internal system pressures, and thus how one influences the other.

System performance and sophistication of analysis has a significant cost, and a balance between risk mitigation and practical implementation is unavoidable. In a commercially competitive climate, the simple economics arising from an absence of agreed-upon design criteria – or worse, the complete absence of a mandate to undertake any analysis at all – mean that this question is likely to be allocated minimum resources. In short, there is little in place to ensure functional and safe buildings; system design is frequently arbitrary and left to chance, and value engineering allows for a small safety margin.

Design from First Principles

In the absence of codified requirements, a responsible design calls for solutions engineered to meet expected functional requirements. The starting point for an internal wind pressure analysis must be the pressure limits at which systems could fail to operate. In Australia, however, even these limits are specified for only a limited subset of building elements, as listed in Table 2. For other aspects of the building, those for which pressure limits are not established, a logical starting point is the typical default design operating pressure or pressure rating (for a no-wind condition), as listed in Table 3.

Building Element	Pressure Limits	Reference
Fire Stair Doors	110 N (Approx. 50 Pa)	AS 1668.2
Lift Doors (Critical for Lift Evacuation)	100 Pa	Lift Manufacturers

Table 2. Pressure limits, as defined in Australia, at which the functional failure of building elements could occur (Source: Murchie Consulting)

Building Element	Typical Pressure
Stair Pressurization / Fan	300 Pa
Bathroom / Kitchen Fan	200 Pa
Standard Plasterboard Wall Type	250 Pa

Table 3. Typical design pressures of building systems (Source: Murchie Consulting)

The differentiation between Pressure Limits and Design Criteria for wind resistance is important here. Wind pressures fluctuate with time, and so it is necessary to specify the probability, calculated from the return period, that a pressure limit will be exceeded over a certain timeframe. Suitable probability depends, in conjunction with the consequence of the failure, on the tolerable level of risk.

Analysis Example 1 - Internal Partitions

Figure 1 showed the in-principle relative magnitudes of typical internal pressure limits and external wind pressures. The case of a single internal inter-tenancy wall separating a windward side apartment and a leeward-side apartment, as illustrated in Figure 5, serves as a useful example of how a default design rating may need to be upgraded based on probability of failure.

Wall ΔP (Pa)	Return Period (days)	Probability (over 1 year)
250	3	100%
500	24	100%
1000	730	39%

Table 4. Return periods at which various internal wall pressures will be exceeded in an example 60 storey building, and the corresponding probability of pressure exceedance over a 1-year period (Source: MEL Consultants)

Figure 6 compares the positive pressures on the windward side of the building for a range of return periods to the 250 Pa pressure rating of a standard plasterboard wall type.

By considering the leeward side negative pressure and appropriate pressure coefficients for dominant openings, it becomes possible to calculate the return period, and thus the probability that the internal wall will be subjected to a particular differential pressure. Example results of such a calculation for a 200 m building in Melbourne are shown in Table 4.

As proposed in Table 1, it seems reasonable to assume that internal wall failure has less severe consequences than failure of the structure or façade. This justifies the application of a lower return period (i.e. higher probability of failure) to the risk assessment. Further mitigation is achieved by the limited conditions under which failure can occur – in this case, for both the windward and leeward side windows to be open while pressures that exceed the wall rating occurred.

It is clear that a standard 250 Pa rated plasterboard wall is insufficient, however, in the absence of codified or agreed-upon design criteria, selection of an appropriate rating depends on project risk tolerance.

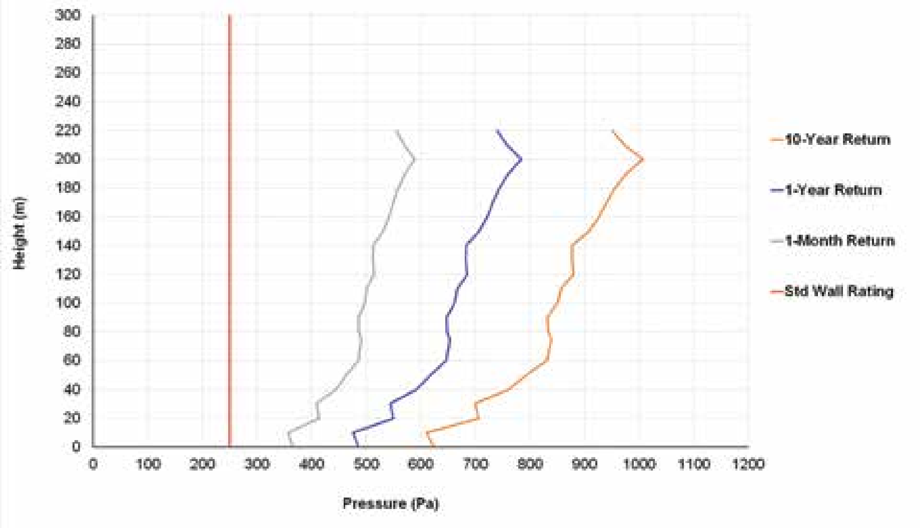


Figure 6. Windward positive peak gust cladding pressures of varying return periods compared to the 250 Pa pressure rating of a standard plasterboard wall type (Source: Murchie Consulting)

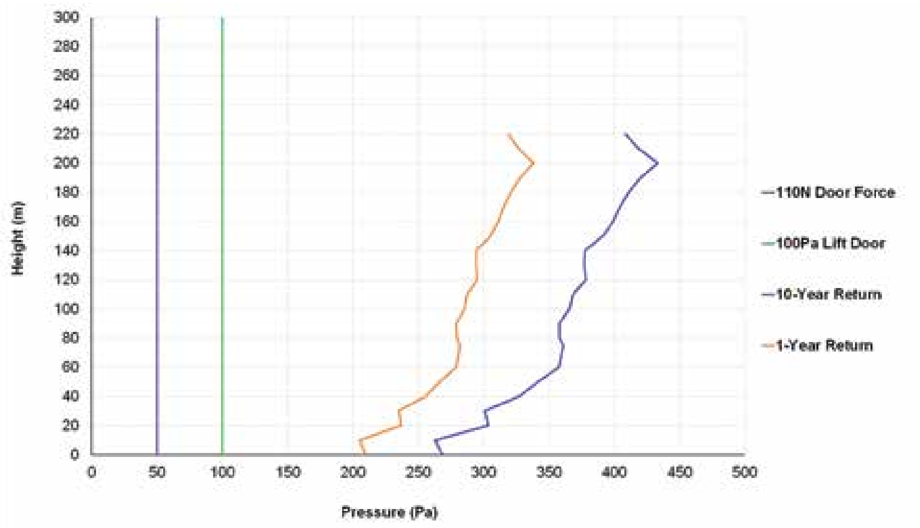


Figure 7. Windward positive hourly mean cladding pressures of varying return periods compared to the low pressure limits on evacuation path doors (Source: Murchie Consulting)

Analysis Example 2 - Stair Pressurization Fans

A comparison of wind pressures to the pressure limits applicable for building life safety systems shows a similar result. As indicated in Figure 7, evacuation path doors (fire stair doors and lift doors) are subject to very tight pressure limits. The building stair pressurization and other smoke control systems must be finely controlled to ensure operation within these limits – no simple task given that even system losses are several multiples greater than the target pressures. Even under ideal circumstances with no wind, it is difficult in practice to achieve expected performance with such systems during a fire alarm condition (Lay 2013).

Stair pressurization systems operate continuously, and shafts inherently provide damping of pressure pulses. This means that, for these systems, it may be more appropriate to consider hourly mean wind pressures instead of the peak gust. Even so, as Figure 7 illustrates, wind pressures occurring with even relatively frequent return periods are considerably higher than the design differential pressures.

Depending on configuration, such as the location of air intakes and outlets, system fans may need to overcome the wind pressures shown (or perhaps even double these), all whilst attempting to maintain acceptable pressure differentials and flows across evacuation path doors (stair doors or lift doors). If the fans cannot adequately control internal conditions, these doors may be impossible to open. Worse, if sufficiently high wind pressures act against the fans, smoke could enter the fire stair.

It is clear that fan sizing for system pressure losses alone is insufficient if the system is exposed to differential wind pressures. In the absence of codified or agreed-upon design criteria, however, selection of an appropriate return period wind pressure to augment fan capacity depends on project risk tolerance. Fortunately, the façade pressure distribution data obtained by wind tunnel testing allows the simultaneous differential pressure between any two points on the façade to be determined, on any elevation, at any height, and for any wind direction. This information can help inform the optimized location of air intakes and outlets to avoid subjecting system fans to unnecessary wind pressures.

Emergency Evacuation

Stair pressurization is a key system to enable safe evacuation during a fire. No tall residential building design would be complete without a comprehensive evacuation strategy, including evacuation modelling. This is particularly important as these new high-rise residential buildings are of a scale that fire brigades in many cities have not encountered before. Ideally, evacuation models should be benchmarked against known past evacuations in comparable buildings and cities to verify that the results realistically reflect the challenges of evacuating a tall building via a narrow congested stair.

In Australia, the inclusion of lifts as an inherent part of the evacuation strategy has only recently become the norm. Where previously the sole priority was to maintain appropriately pressurized conditions in the stair, this evolution introduces the need to maintain acceptable conditions in a portion of the apartment corridor as well. Openings in the façade, however, whether on the windward side, leeward side or both, result in a wide and unpredictable range of potential corridor pressure conditions and flow paths. In tall ventilated residential buildings with lift evacuation, the only practical solution is often to consider the introduction of smoke lobbies, which isolate and protect the zone around lifts and stairs at each level.

Example Design Criteria

The requirements and risk tolerance of individual projects vary. In the absence of code and regulatory requirements or agreed-upon design criteria, it is necessary for engineers to undertake a full and formal risk analysis and a comprehensive risk-based design for each building individually, considering conditions on a case-by-case basis.

Table 5 lists example return periods that can serve as a starting point for such an assessment. These have been achieved by systems that several Melbourne high-rise residential buildings have adopted with a view to manage wind risks in an economically feasible way. Are these probabilities of failure tolerable? Further formal risk analysis would be needed to determine this, but they nevertheless certainly represent an outcome significantly better than a default code-compliant design that ignores internal wind pressure effects.

Wind Mitigation Strategies for Safety

With a threshold of tolerable risk and a corresponding wind return period established for each wind-affected building element, engineers must integrate wind mitigation measures into the various building components and systems.

In Australia, a number of high-rise buildings have been built in recent years for code compliance only, incorporating little at all in the way of internal wind pressure mitigation.

Building Element	Return Period of Exceedance
Evacuation / Smoke Control Systems	10-Year Hourly Mean
Internal Partition Integrity	1-Year Peak Gust
Ventilation System Operation	1-Month Hourly Mean

Table 5. Example return periods of pressure exceedance achieved by wind mitigation measures in several Melbourne tall buildings, potentially serving as a starting point for new agreed-upon design criteria (Source: Murchie Consulting)

Nevertheless, most are currently adopting a combination of measures such as snap-shut windows, up-rated internal walls, door seals, compartmentalized stair pressurization shafts, and the selection of fans with a degree of spare capacity, for example. Broadly, the tendency is to mitigate wind pressures through configuration and upgrading of the affected components themselves.

An alternative approach is to mitigate wind pressures at the building envelope through automation of the façade openings. In effect, this turns an otherwise ventilated tall building into a more conventional sealed building under adverse wind events and in the case of a fire. The cost of such a system is significant, but it can be offset by a reduced need for internal pressure-mitigating measures – savings in both material costs and in sellable area.

Design Process

With no code criteria to guide this aspect of tall building design, it is more important than ever that the various experts providing input collaborate closely, in particular the wind engineer, fire engineer, code consultant, façade engineer, mechanical engineer, and architect. In essence, the design process for tall ventilated residential buildings with operable facades involves a new step, one not previously needed when tall buildings were sealed: a formal risk assessment of internal wind effects.

Evacuation modelling and an evacuation strategy developed by the fire engineer and code consultant establish system functional requirements, such as the need for lift evacuation, and probabilistic decision tree modelling can help determine tolerable probability of system failure. These results can serve as design criteria. Similarly, the cladding pressure wind tunnel tests conducted by the wind engineer provide the external wind pressures that need to be mitigated.

The most effective way to bring these inputs together is to convene a series of targeted face-to-face workshops. The various potential pressure transmission paths must be identified, and the return periods with which various differential pressures will occur must be calculated. Expected differential pressures on individual building systems and components, in terms of magnitude and tolerable return period, then drive required wall ratings, fan capacity, and the need to integrate additional wind mitigation measures in the architectural, façade, and mechanical design.

Future Directions

In cities around the world, the urban landscape is evolving. As high-rise residential buildings with operable ventilating façades continue to grow in height and number, engineering practice too must evolve and respond to emerging challenges. Wind pressure effects on components and systems within a building are one such new challenge, and they pose real risks to safety and amenity – two of the most fundamental reasons that dwellings exist in the first place. These are large buildings, each providing housing for thousands of people and together redefining the form of urban habitat for decades if not centuries to come.

Where the codes are not keeping step, responsible engineering must pick up the slack. The key is awareness. At each step of the building development process, competitive pressures drive maximum efficiency – design that pushes the limits to create technical and economic solutions that only yesterday would have been thought impossible. Real progress, the kind that has a truly positive and profound impact, results only from the fully informed engagement and participation of all stakeholders. No responsible professional – no engineer, no architect, and no developer – would willingly ignore a safety risk, and similarly every professional understands the need to optimize value in quality. This, however, is only possible on a level playing field, where the issues are recognized and understood by all.

Ultimately, the solution to present regulatory shortcomings must be an update to building codes, both in Australia and internationally. Setting design criteria for a tolerable threshold of risk is beneficial both technically and commercially. In the meantime, more work is needed to better understand the probabilistic relationship of the various inputs to an internal pressure risk assessment – wind, fire, occupant behavior, control options. For the more mechanically oriented, there is also a tremendous opportunity for innovation in technical solutions including building control and façade automation.

References:

AS 1668.2:2012, **Australian Standard – The use of ventilation and airconditioning in buildings**, Part 2: Mechanical ventilation in buildings, Standards Australia International Ltd., Sydney.

AS/NZS 1170.2:2011, **Australian / New Zealand Standard – Structural Design Actions**, Part 2: Wind actions, Standards Australia International Ltd., Sydney and Standards New Zealand, Wellington.

Lamande SK, Xu, Z & Bekele S 2013, **'The effect of Varying Opening Area in a Windward Wall on the Internal to External Pressure Coefficient Ratio of a High-Rise Apartment'**, 16th Annual Wind Engineering Society Workshop, Brisbane.

Lay, S 2013, **'Pressurization systems do not work & present a risk to life safety'**, Case Studies in Fire Safety 1 (2014), pp. 13-17.

Melbourne, WH 1978, **'Criteria for Environmental Wind Conditions'**, Journal of Industrial Aerodynamics 3 (1978), pp. 241-249.

General Headquarters of Civil Defence, Ministry of Interior, United Arab Emirates 2011, UAE Fire and Life Safety Code of Practice.