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Design Considerations and Implication of Stack Effect in High-Rise Developments in Hot and Arid Climates

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ABSTRACT

The development of high-rise towers in more extreme climates has highlighted the effect of interaction between internal and external conditions on the air movement within a building. This phenomenon is largely caused by the temperature difference and the resulting density variance associated between the two regions. During the early design process the effect of wind conditions on the internal occupant comfort including temperature and internal wind speeds, operational implications such as lift door pressurisation, wind entry and mechanical ventilation performance as well as the potential health and safety issues including control of air movement from smoking areas to the downwards air movement of smoke during fire scenarios (associated with reverse stack effect) needs to be understood. This paper investigates the implications of high-rise design on the internal flow patterns with a particular focus on the effect of non-uniform built form towers.

1. Introduction

The number of high-rise and supertall buildings being constructed globally has been increasing exponentially for the last few decades. At the end of 2017, the average height of the world's tallest one hundred towers was 372m, and saw the first supertall tower (300m+) not able to be considered on the World's Tallest Building list (Huachung International Plaza Tower 1). This trend in the height of constructed buildings can be noted in Figure 1 (CTBUH, 2017). Furthermore the location of the tallest buildings has also diversified significantly. In the 1940s, the tallest towers were largely contained throughout North-America, however in 2017, this only accounts for a small proportion, with the majority of tall buildings now located throughout Asia and the Middle East regions. The location of high-rise and supertall buildings located in these more extreme climate regions has increased the awareness of the internal environment due to stack effect. Some of these supertall buildings are located in regions which have experienced external temperature ranges of greater than ±40^{o}C within the last 12 months.

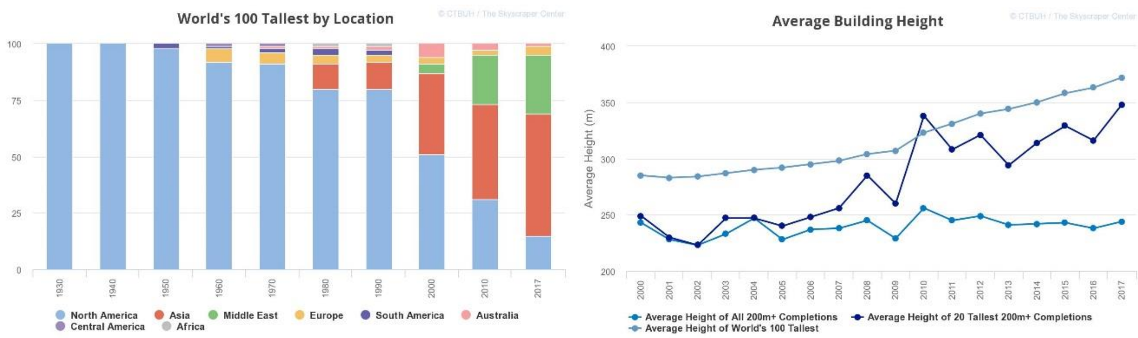

Figure 1: Average High Rise Building Heights and Location Variance (CTBUH, 2017)

Stack effect is a buoyancy driven phenomenon that direct results from the temperature difference between the internal and external environment leading to a pressure driven flow throughout the building. The directionality of the internal air movement depends on the external temperature compared to the internal environment. The stack effect can have a profound impact on the operation of a building including affecting thermal comfort conditions, wind conditions at entry points, lift operations, smoke control design and mechanical plant operations to note a few.

2.1 Effect of Local Climatic Conditions

The local climatic conditions are the primary governing drivers for stack effect to occur within a building and also drives the directionality of the flow. For projects located in cold climates, the heated inside air rises up any vertical shafts (lift and services) and flows out of the building at the upper levels through building leakage or mechanical openings. The adverse effect of this airflow at ground floor is typically experienced at the entry points as the cold outside air is drawn into the building via any ground level entry points, reducing the benefit of any heating in this zone and negatively impacting heating costs. The effect can also be experienced at any narrowed door openings associated or linked to the lift lobby space as a faster moving airflow.

On the other hand, for developments located in hotter regions, the flow directions are reversed, with the internal air movement falling down the vertical shafts due to air density differences between hot and cold air. The generic flow patterns are illustrated in Figure 2.

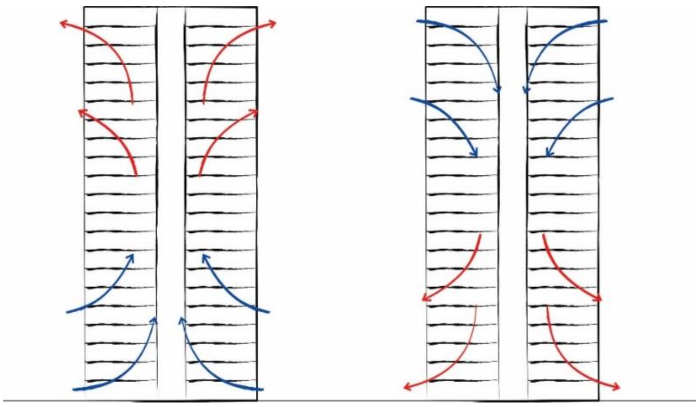

Figure 2: Stack Effect (Left) and Reverse Thermal Stack Effect (right) Flow Directions

2.2 Buoyancy Driven Flow

The pressure difference due to the stack effect at height h is;

$$\Delta P_s = (\rho_o - \rho_i) g (h - h_{NPL}) \tag{1}$$

$$\Delta P_s = \rho_i g (h - h_{NPL}) \frac{(T_i - T_o)}{T_o} \tag{2}$$

ΔP_s	Pressure difference due to stack effect	T	Average absolute temperature ($^\circ C$)
h	Height of observation (m)	h_{NPL}	Height of neutral pressure level (m)

2.3 Wind Driven Flow

In addition to the buoyancy driven forces of stack effect, it is also important to consider the effect of the external wind pressure acting on the subject development, in particular to openings and/or cracks over the façade. Due to the atmospheric boundary layer wind profile, there is a notable difference in wind speeds experienced between the lower sections and upper sections of a tower, Furthermore, the location of external openings (including mechanical vents) on the façade with respect to the prevailing wind can have a significant impact on the infiltration and exfiltration of the external winds. It is also noted that while ideally the façade of a building should be air-tight, this is never the case and hence leakage through the facade occurs, which can vary significantly.

2.4 Neutral Pressure Level

The height at which the interior and exterior pressures are equal is called the Neutral Pressure Level (NPL) (Tamura and Wilson 1966, 1967). Above this point (during the warmer months), the interior pressure is greater than the exterior; below this point, lower exterior pressure causes airflow out of the building. Available data on the NPL in various kinds of buildings is limited. The NPL in tall buildings varies from 0.3 to 0.7 of total building height (Tamura and Wilson 1966, 67).

The design of high-rise towers makes the prediction of this location somewhat complicated. This is due to the internal layout which allows for the transfer of airflow within the building, such as lift shafts, stairwells, internal ducting (mechanical and services), layouts, external opening locations and the overall built form. The location of significant openings on the built form causes the NPL to shift in the direction of the opening due to the reduction in flow restriction across the building envelope.

The NPL has largely been described in terms of a simplified 2D built form with uniform plan levels as noted in Figure 3. This however is not the case in the majority of building designs around the world, with varying floor plate designs, level heights and also the inclusion of multiple towers atop a larger podium. All of these factors can affect the internal movement of air flow within the building.

From research undertaken at Windtech on a number of tower designs, it has been found that a main driver in the NPL is the internal volume of the building connected to the vertical flow path. The NPL level was therefore found to be related to the overall internal connected volume and the difference between the external and internal temperatures associated, as noted in Equation 4, which is a derivation of work by Tamura (1967). This provides the volumetric neutral pressure level of the building envelope which can then be used to derive the NPL height above ground.

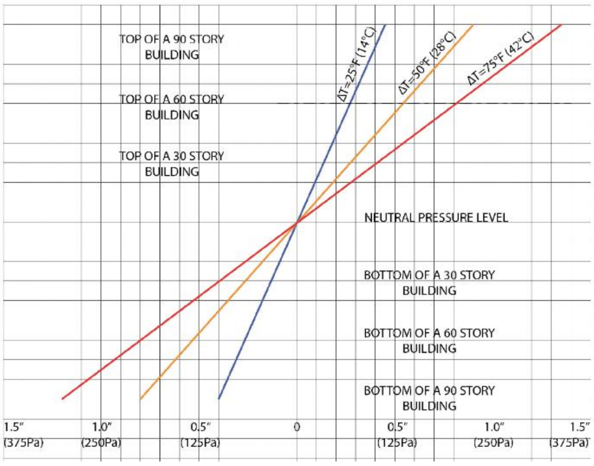

Figure 3: Theoretical Thermal Stack Pressure Gradient in a Uniform Building (ASHRAE, 2015)

As part of the verification process for this equation of the predicted NPL level with varying floor volumes, onsite measurements were made within the JW Marriott Marquis, Dubai as part of remedial site works for the client as a third party. This will be discussed in further detail in Section 3.

$$\mathrm{NPL_v} = \frac{IV}{1+\left(\frac{T_o}{T_i}\right)} \tag{4}$$

NPL_v	Neutral Volumetric Pressure Level (m^3)	T_i	Internal Temperature (K)

T_O	Internal Temperature (K)	IV	Internal Volume connected to vertical shaft (ieg lift shaft) (m^3)

3. Case Studies

3.1 Built Form Variation

The overall building envelope of a development has a significant effect on the stack effect. This is largely due to the impact on the NPL as well as the internal flow path throughout the building. An investigation has been undertaken by Windtech to understand the effect of pressure variance with height for two types of development; a twin tower development atop a large common podium (JW Marriott Marquis) and a stepped tower design with a central void through the built form (Imperial Avenue). Both of these developments are located in Dubai and hence would be expected to experience reverse thermal stack effect due to the temperature differences. For the Dubai region, during the warmer summer months, the difference between the external and internal air-conditioned space of a building will be generally greater than 20°C. This difference generates an air flow within the building, with the effect dependent on the height of a single connected volume (lift shaft) and connected areas (levels). However during the winter months, this temperature difference becomes quite small and hence reducing the effect experienced.

JW Marriott Marquis, Dubai

The JW Marriott Marquis development, located in Business Bay in Dubai consists of two towers atop a common podium. The podium consists of an interconnected volume which extends towards the west of the site, creating a significant internal volume. Prior to the opening of the hotel, a significant reverse thermal stack effect was noted within the ground floor lobby space of the south tower. Windtech subsequently undertook a detailed onsite review of the development considering all aspects including the mechanical system, opening locations and podium design. As part of a site survey, the flow directionality within the lift shaft over the height of the tower was recorded to verify the NPL location for the tower. This was found to be at the top of the podium, approximately 42m above ground, which is certainly not aligned with “typical” stack effect assumptions. Measurements made within the ground floor lift lobby noted air flow velocities of over 5m/s. A detailed analysis undertaken to determine a volumetric NPL was found to correlate with the on-site measurements. This highlighted the implications of significant podium volume on the NPL location and the lift lobby conditions experienced.

Numerous mitigation measures were subsequently developed to minimize this affect. One optional consideration was the reduction of the size of the interconnected podium via compartmentalization. While this would increase the height of the NPL for the tower, it would also reduce the pressure equalization required for the podium levels through the lift lobbies where the most adverse conditions were noted.

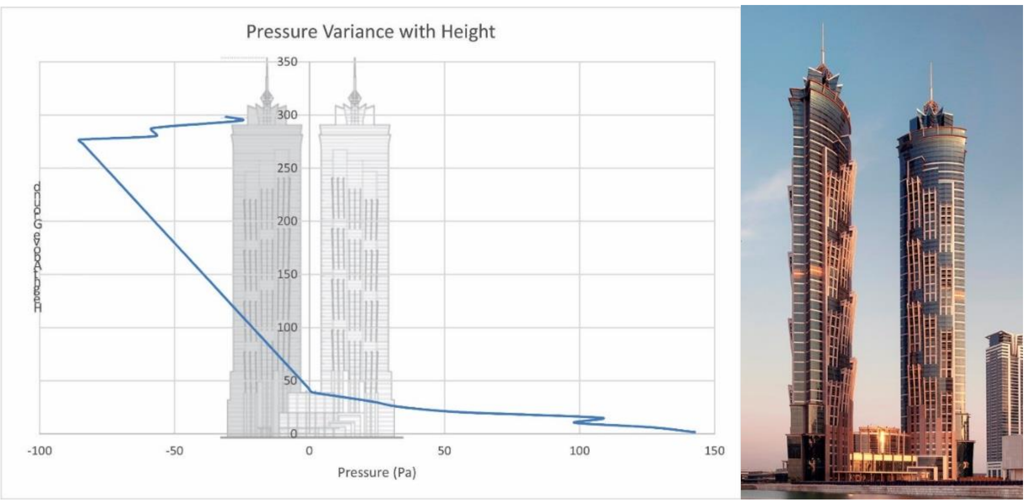

Figure 4: Pressure Variance with Height for the JW Marriott Marquis, Dubai (South Tower)

Imperial Avenue, Dubai

The inclusion of architectural (and structural) features such as linkages between towers or voids through building forms creates unusual vertical flow paths within the tower in terms of stack effect. The Imperial Avenue development in the Burj Khalifa precinct in Dubai is one such example. As noted in Figure 5, the overall tower form steps at the upper levels, while a large void through the tower form is included just above the podium of the development. This subsequently creates a vertical lift shaft up the entire height of the tower, while a secondary lift shaft stops at just over the half building height. Due to the complexity of this arrangement additional comparative modelling was undertaken using CONTAMW3 to understand the pressure distribution between the two main interconnected risers. As noted in Figure 5, the inclusion of the void through the tower form causes a step change in the pressures experienced, effectively increasing the height of the NPL in the tower. The inclusion of additional vertical risers can also be noted to reduce the differential pressure at the lift lobby area (compared to a single lobby design approach), however has a significant step increase in pressure as shafts are dropped off at the upper levels of the tower.

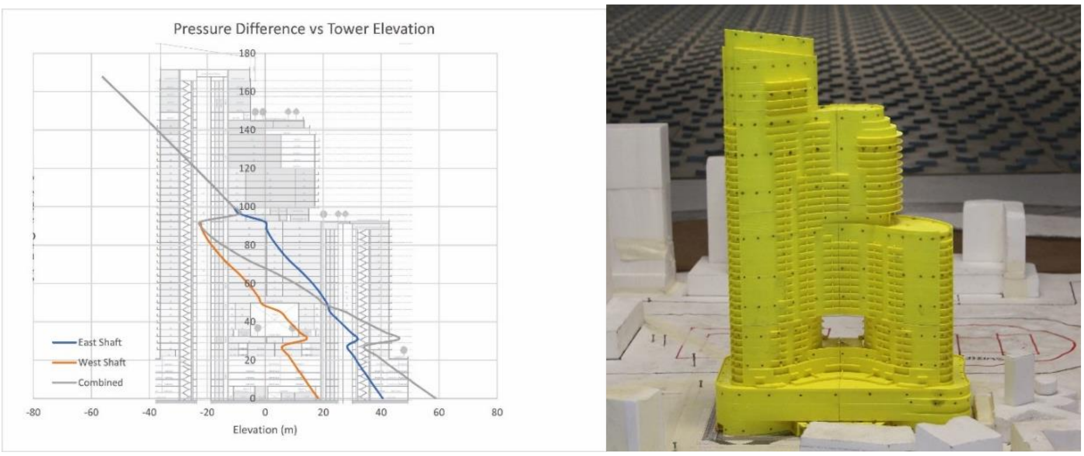

Figure 5: Pressure Variance with Height for the Imperial Avenue, Dubai

4. Considerations and Design Challenges

The effect of stack effect within a building can have notable adverse effects in the operation of tall buildings, including the following:

- *Elevators:* The lift shaft acts as a vertical flow path through the building with the pressure over the lift door sufficient to cause malfunction or issues with the guiderails. This can also impact the operation of the lift within the shaft itself and impact on the piston effect.
- *Door Operation:* Due to the increased pressures on levels further away from the NPL, this can cause issues with swing door operation, including difficulties opening or slamming closed.
- *Uncomfortable Air Flow:* this is generally experienced in the lift lobbies or nearby corridors, as well as on entry to the lift cart and considered as a “draft” by occupants (ASHRAE 2013).
- *Noise Generation:* Depending on the size of gaps, this can cause whistling, generally associated with the lift shaft or entry doors to apartments.
- *Impact on Heating and Cooling:* The internal air movement results in the undesired heating/cooling transfer, drawing in external unconditioned air into the building.
- *Fire/Smoke Strategy:* A significant impact can occur on the proposed smoke/fire strategy for the building, increased smoke propagation rates and unusual smoke flow patterns.

Considering stack effect during the design process is an important step to help prevent or minimize the impact of the abovementioned aspects. This has been discussed in numerous studies Jo et al (2007), Koo et al (2004) and Simmonds (2013, 2015) and summarized as follows:

- *Façade Leakage:* The permeability of the façade of the building envelope has a significant effect on the stack effect. By designing the building to be more "air tight" reduces the infiltration/exfiltration through the façade (Mijorski et al, 2016).
- *Lift Lobby:* The lift shaft is one of the primary vertical flow paths for stack effect, hence separation of the lift lobby from the main floor of the building is of significant benefit, particularly at the upper and lower levels of the building which are furthest from the NPL.
- *External Entrances:* This affects the internal pressurization, particularly during extreme wind events. Inclusion of effective airlocks at these openings and lift lobby spaces should be considered. This should include consideration for expected foot traffic.
- *Lift Shaft Location:* The location of the lift shaft on the external perimeter of the building form can increase in the stack effect as a glazed lift shaft will heat the internal air layer driving vertical flow.
- *Internal Pressurisation:* Internal pressurization of key areas can help minimize the infiltration of external air and also reduce the pressure differential on these levels. Forcing air into the lift shaft can reduce the stack effect by altering the temperature differential along the flow vertical path. This is currently already implemented in some regions.
- *Compartmentalisation:* Developing vertical separation of the envelope will reduce the distance away from the NPL of a building and hence the magnitude of the pressure developed. This could be done through separate elevator shafts which serve different height sections of the tower. Note that these would need to be separated at the connecting level also. This separation should also be considered for vertical services/risers.

5. Conclusions

The stack effect is a buoyancy driven flow within the building envelope that results from a significant temperature differences between the internal and external environments. This paper investigated the effects of stack effect on and practical solutions for more complex building envelopes which occur more frequently than the idealistic uniform tower form. The implication of inter-connected podium designs on the internal air flow conditions of a development was noted, with considerations for compartmentalization of the podium design through lift lobby air-locks as an important design aspect. Furthermore, the location of lift shafts on external facades, while ideal from a visual perspective, can adversely contribute to the stack effect within a tower due to the thermal heat transfer through the façade itself. It is important to consider the effect of stack effect and reverse stack effect for high-rise building developments as part of the schematic design phase. This would enable design changes to be incorporated where necessary and also minimize the potential for adverse internal air flows and pressure related problems once the building has been completed.

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