WIND & THE skyscraper

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Introduction: the rise of the skyscraper

In New York 1852 the invention of a product of engineering simplicity, spurred on by the industrial revolution, redefined the word 'tall' in architecture forever- the safety elevator. This acted as the catalyst for a revolution in American real estate; where the higher floors of city buildings had once been used for servants' housing, the elevator shifted the opinion of the wealthy so that these became the most sought-after real estate available. Penthouses were now marketed as the glamorous top-floor apartments with better natural light and cleaner air. And so, an era of 'tall' buildings began, mobilising the birth of the skyscraper.

Nearly two centuries later, skyscrapers are the hallmark of most cities' skylines and with such significance comes the readiness of engineers to develop new building materials and techniques, in order to make taller distinctive structures. This includes the development of ultra-strong concrete and steel, advanced computational techniques and new construction systems. However, as a result of such developments, recent generations of skyscrapers are so lightweight, flexible and lowly damped that their sensitivity to wind effects has become a critical component of the design process.

The dynamic nature of wind loads is known to induce vibrational motion within a skyscraper, causing structural damage and posing a threat to the occupants of higher floors. It is hence important to explore the effect of aerodynamic modifications on super-tall buildings, such as corner softening, tapering, porosity and twisting to mitigate wind excitation and improve the safety and habitability of the skyscraper.

Figure 1. The world's first skyscraper was the Home Insurance Building in Chicago, erected in 1884-1885. (CAPC, 2020)

The Wind Effect

A structure immersed in air is subject to aerodynamic forces due to the relative motion between the body and gas. For tall buildings, these forces take the form of drag and lift in the along-wind and across-wind directions respectively (Gordan & Izadifar, 2014). The latter typically dominates the former, however, aerodynamic mitigation techniques act to reduce both.

Drag

Here, in the context of fluid dynamics, drag refers to forces that act in the direction of mean flow and can be decomposed into two components; those caused by the differences in pressure on the windward and leeward faces of the building (pressure drag) and those caused by viscous shear stress (viscous drag) (Adrian & Smits, 2020). The magnitude of the drag force F_d is estimated to be proportional to the square of the relative flow speed u, with a dependence on the projected frontal area of the object A and the mass density of the fluid ρ as well as the drag coefficient c_d, a dimensionless factor of proportionality related to the geometry of the object (Batchelor, 1967).

The drag coefficient takes into account both the pressure and viscous drag, and can be expressed mathematically as

$$c_d = \frac{1}{\rho u^2 A} \iint d\boldsymbol{A}\,(p - p_o)(\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{\imath}}) + \frac{1}{\rho u^2 A} \iint d\boldsymbol{A}\,(\hat{\boldsymbol{t}} \cdot \hat{\boldsymbol{\imath}})\,\tau \qquad (1)$$

for a body where: p is the pressure at the surface with unit area $d\boldsymbol{A}$ and p_o is the pressure at a far distance from the same surface, $\hat{\boldsymbol{n}}$ and $\hat{\boldsymbol{t}}$ are the normal and tangential vectors to $d\boldsymbol{A}$, $\hat{\boldsymbol{\imath}}$ is the unit vector in the direction of free stream flow and τ the viscous shear stress (Sighard, 1992). This decomposition is favourable as it emphasises the two components of drag; with the first integral equal to the pressure drag coefficient and the second, the viscous drag coefficient.

Due to the angular dependence of the dot product between $\hat{\boldsymbol{n}}$ or $\hat{\boldsymbol{t}}$ and $\hat{\boldsymbol{\imath}}$ in the drag coefficient equation, it is evident that the type of drag is determined by the angle of attack and the shape of the body. For a streamlined body, where the frictional component dominates the drag coefficient, there is a small angle of attack between the body and the fluid flow. Thereby, the layers of the fluid close to the boundary surface experience a weak pressure gradient and remain attached, producing a small wake (Hucho, Janssen, & Emmelmann, 1975). With an increasing angle of attack comes an increase in magnitude of the pressure gradient associated with the boundary surface. In the case of a skyscraper, a bluff body as opposed to streamlined, the pressure gradient on the leeward face of the building can often become sufficiently strong so as to cause the fluid flow to detach from the surface and form eddies (Adrian & Smits, 2020). A large wake is formed with a great pressure loss as a result of the eddy formation; hence pressure drag becomes the dominating component of the net drag coefficient. The motion displayed by a building in the along-wind direction is thereby mainly a result of the manifestation of the net force as pressure differences on the windward and leeward faces of the building and varies with fluctuations in the approaching flow (Amin & Ahuja, 2010).

Reynolds Number

Briefly, the Reynolds number of flow R is a dimensionless quantity used in fluid mechanics to predict the behaviour and patterns of flow in a fluid. It is defined as the ratio of inertial forces to viscous forces

Figure 2. The plume from a candle is initially laminar, but transitions to turbulent flow in the upper third of the image. The Reynolds number can be used to predict where this transition occurs. (Settles, 2020)

within a fluid and can be mathematically expressed as

$$R = \frac{uL}{v} \quad (2)$$

Where L is a characteristic length, say the width of a building, and v is the kinematic viscosity of the fluid (Sommerfeld, 1908). At low Reynolds numbers, laminar flow occurs; this is where the dominating viscous forces generate a fluid with smooth layers and a lack lateral mixing. Whereas, turbulence (and hence vortex formation) occurs at high Reynolds numbers due to variations in the fluid's speed and direction and the flow is hence dominated by inertial forces.

Vortex Shedding

Across-wind motion is determined by lift forces acting in the direction perpendicular to mean flow. In the case of bluff bodies, such as skyscrapers, lift fluctuates due to vortex shedding: a phenomenon of oscillating flow.

When a wind flows with sufficiently low Reynolds number passed a bluff body with a plane of symmetry in the flow direction, two vortices form behind the body; standing and symmetrical in nature (Buresti, 1998). With a steep pressure gradient on the leeward face, the boundary layers separate from the body on each edge and contour around the region containing the pair of vortices, recombining further downstream to form a narrow wake of steady state. The size of the vortex containing region is proportional to the Reynolds number of the flow whilst in its steady state.

Increasing the Reynolds number beyond a critical value (specific to the geometry of the body) leads to a transition from a steady to an unsteady state in the wake.

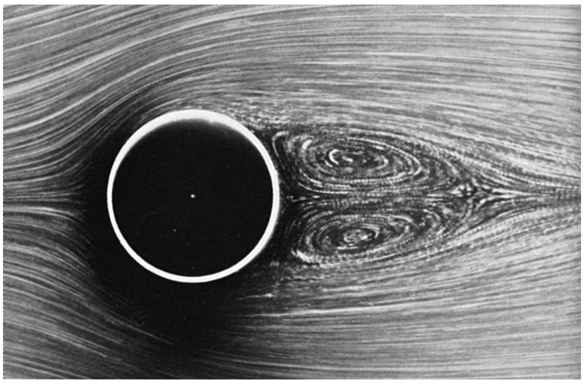

Figure 3. The formation of a steady state wake behind a cylinder. Since the Reynolds number of the flow is sufficiently low, the vortices have not begun shedding. (Gutierrez-Miravete & Langley, 2020)

An equilibrium flow can be reached, however, this time with a time-dependence which is characterised by the periodic shedding of the vortex from either side (Buresti, 1998). The frequency of vortex shedding f is related to the Strouhal number S, a constant typically in the range of 0.1 to 0.3, by

$$f = S\frac{u}{b} \quad (3)$$

where b is the width of the body and u is the flow velocity (Irwin, Kilpatrick, & Frisque, 2008). Due to the low-pressure nature of vortices, the body will tend to move toward the side with a vortex still present. In the case of a building, it is hence subjected to periodic pressure loading which results in a fluctuating across-wind force. Alone, the magnitude of the force is not great enough to generate substantial motion; however, when the frequency of shedding nears the natural frequency of the building, resonance occurs causing an amplified across wind response driven by the energy of the flow.

By rearranging equation 3 with the natural frequency of the building replacing the shedding frequency, one can solve for the wind velocity at which resonance occurs,

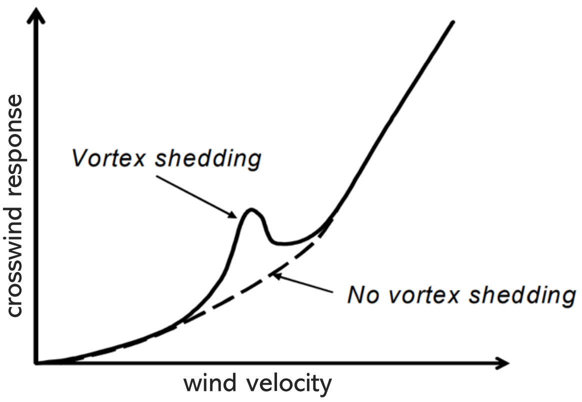

Figure 4. Effect of Vortex Shedding on response (Irwin, Kilpatrick, & Frisque, 2008).

this will align on the x axis with the peak seen in the crosswind response in Figure 4. Traditionally, the approach to reduce crosswind response was to increase the natural frequency of the building by adding stiffness; shifting the peak further enough to the right that the corresponding wind speeds were too high to be of concern. However, due to the high financial cost of this method, aerodynamic mitigation techniques are becoming increasingly more common. These techniques aim to lower the height of the peak, and hence the amplitude of the building's vibrations, through four methods: tapering, softening of corners, increasing porosity and twisting.

Tapering & Setbacks

The modification of a building's geometry, such as varying the cross-sectional width along its height and reducing the plan area on upper levels by cutting corners, can reduce the excitation caused by wind. This is due to the dependency of the frequency of vortex shedding on b, the width of the building, in Equation 3. The flow pattern is altered around the building, with vortices shedding at different frequencies along different heights. Hence, there lacks coherence in the formation of wake fluctuations along the height of the building, causing a dramatic reduction in periodic loading and so crosswind forces. In a similar fashion, varying the shape of the cross-section changes the value of the Strouhal number S in Equation 3 and hence the vortex shedding occurs over a wider range of frequencies (Irwin, Kilpatrick, & Frisque, 2008).

The effectiveness of tapering to reduce wind excitation was investigated by Kim and You (Kim & You, 2002) with wind tunnel tests. They used building models of 400mm height with tapering ratios of 5%, 10% and 15%. In the along-wind direction their results showed a reduction of 20% in pressure coefficients and in the across-wind direction the maximum reduction of across-wind forces was 30% for an urban terrain. Tapering was shown to be most effective when the wind flow was normal to the windward face.

Figure 5. The Shard exploits the advantage of reducing the width of cross section along the height to minimise the wind induced vibrations at the top of the building. (ArchDaily, 2020)

Corner Softening

Older generations of skyscrapers are typically square or rectangularly shaped, however, these shapes are very vulnerable to vortex-induced forces and drag forces. With new technology, it has been shown that 'softening' modifications made to the corners of a building can substantially reduce such forces. Known as 'minor modifications', they have little effect on the architectural and structural design. These modifications include chamfered corners, recessed corners and rounded corners and work by narrowing the width of the wake by promoting the reattachment of the separated layers of flow.

Corner modifications and their aerodynamic impact is often studied through Computational Fluid Dynamics (CFD), as the traditional wind tunnel 'trial-and-error' approach proved too expensive for the design of aerodynamic shapes. Through advances in computing power; aerodynamic optimisation methods are more important than ever. In a study performed by Elshaer et al. (Elshaer, Damatty, & Bitsuamlak, 2014) a rectangular cylinder of square cross-section, with length 50mm, was used in a CFD simulation to measure wind velocity profiles and drag coefficients. Along with sharp corners, single and double recessed corners, chamfered corners and rounded corners were also investigated.

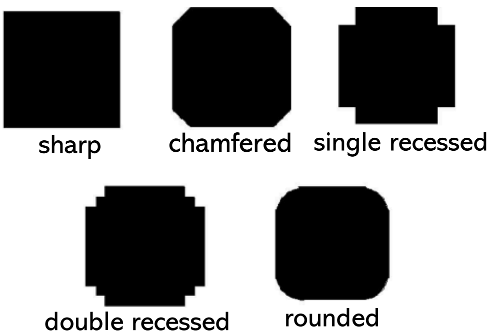

Figure 6. Cross-sections for studied shapes. (Elshaer, Damatty, & Bitsuamlak, 2014)

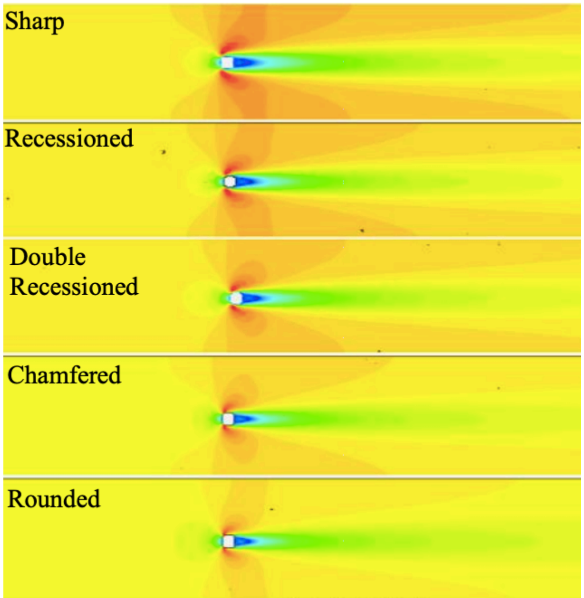

Figure 7. Velocity profiles for the shapes. With the velocity magnitude scaled to a colour spectrum, with blue=0m/s and red=14m/s (Elshaer, Damatty, & Bitsuamlak, 2014)

Figure 7 shows the velocity magnitude profiles around the different cornered shapes. By examining the size of the orange and red zones, one can notice that the sharp-edged square has the widest and longest wake, which leads to higher velocities at the sides of the body. These velocities are reduced most by the rounded corners, followed by chamfered, then double and single recessed. With a reduced wake, we can suspect there is smaller along-wind forces as a gentler pressure gradient is present. Elshaer et al. verified this by calculating the drag coefficient through the use of Equation 1 in their simulation and showed a reduction for all shapes in comparison to the sharp-edged square.

SHAPE	C_D
Sharp	1.88
Single-recessed	1.46
Double-recessed	1.41
Chamfered	1.20
Rounded	1.18

Table 1. Drag coefficients for studied shapes. (Elshaer, Damatty, & Bitsuamlak, 2014)

In Table 1 one can see the shapes show the same order in effectiveness for reduction in the drag coefficient as in reduction in the size of wake zone. The drag coefficient had a maximum reduction of 40%, from sharp corners to rounded corners.

Increasing Porosity

The addition of openings to a building promotes the bleeding of air through the building and is another means of aerodynamic improvement by reducing the across-wind forces. By allowing air to bleed into the wake and into the separated region of flow around the wake, the formation of vortices becomes 'weakened and disrupted' (Mooneghi & Kargarmoakhar, 2015).

Figure 8. 432 Park Avenue, New York. This Skyscraper is divided into seven vertical segments, each with 12 occupied floors. Between each segment is a two-story open section without any windows to allow air to flow through. (Peel, 2020)

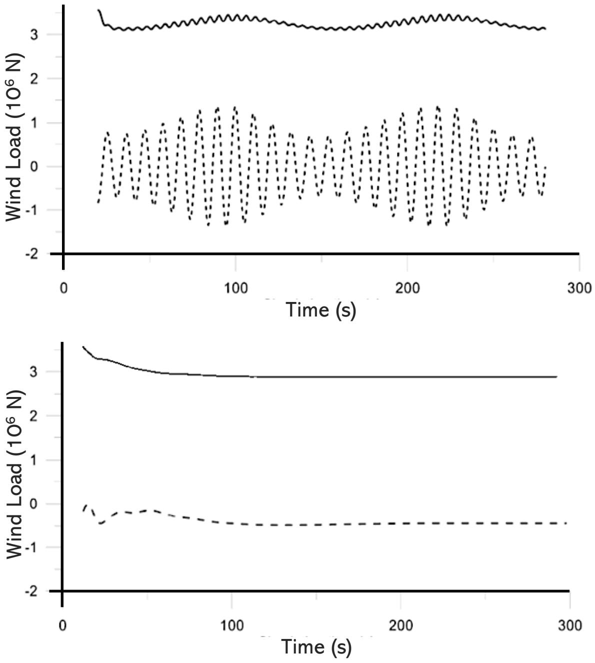

Figure 9. The time history of wind load on the straight tower (top) and twisted tower (bottom). (Tang, Xie, & Felicetti, 2016)

Twisting

By far the most modern aerodynamic mitigation technique is the twisting of architectural form. With new advances in design technology and building materials this approach is becoming increasingly more popular.

The twisting technique is effective in reducing vortex-shedding induced excitation, as opposed to reducing along wind drag. Since the cross-sectional geometry varies with height, the coherence of vortex shedding is lost and hence the instantaneous across-wind forces are of different values and directions along the length of the building. They generally cancel out or at least reduce one another, decreasing the chances of wind induced vibration (Amin & Ahuja, 2010).

A CFD model was built for a straight tower with dimensions 30m x 30m x 180m, and was used to calculate the along-wind and across-wind loads over 300 seconds with a wind velocity of $30ms^{-1}$ (Tang, Xie, & Felicetti, 2016). Tang et al. recorded, as expected, that the wind loads in both directions fluctuated periodically with time, with an average drag force of $3.29x10^6$N and an average lift force of zero but with a large peak value of approximately $1.5x10^6$N (this should be zero in a steady state). When repeated for the same tower with an 180° corkscrew twist, there was a dramatic change in results for the across-wind load. The drag force only showed a 7.6% reduction in magnitude; however, the across-wind load became flat and eventually unfluctuating, as seen in Figure 9 with an average value of $-0.4x10^6$N, having a non-zero value only due to its non-symmetric nature.

With the expectation only heightening for skyscrapers to become more sustainable and greener; the incorporation of twisting into the design of their façades is dramatically increasing in frequency. The reduction in wind load on a building as a consequence of this technique makes the construction more economically sustainable. For example, the Shanghai Tower's twisting façade reduced the wind load on the building by 25%, allowing $58million to be saved in the cost of structural material (Phaidon, 2020).

The Future of Skyscrapers

Skyscrapers have evolved remarkably since the invention of the safety elevator in 1852; creating a new urban landscape from concrete, steel and glass. Hong Kong and New York already have 355 and 280 skyscrapers rising above 150 feet respectively. And as population density in urban areas only continues to grow, there is an ever-increasing need for buildings that rise instead of spread to provide residence to their inhabitants.

Figure 10. Turning Torso in Malmö, Sweden. Regarded as the first twisted skyscraper in the world, with completed construction in 2005. (Tang, Xie, & Felicetti, 2016)

However, as skyscrapers in many ways defined the 20th century; climate change has come to define the 21st and skyscrapers are among the initial targets that urban developers are setting out to adjust. Energy generation and environmental factors are becoming a part of the primary considerations in the design process of skyscrapers. Just as the use of a twisting façade has become more common in the past decade, so has the incorporation of wind turbines into the structure of a building. Using renewable technologies to create energy efficient skyscrapers was first demonstrated with Bahrain's World Trade Centre, which hosts three commercial sized turbines to generate 15% of the building's energy. So, with an incredible amount of research already performed into aerodynamic mitigation techniques; perhaps the next generation of architects and engineers will view the wind as a friend, rather than foe.

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