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The effects of geometrical changes of tall buildings on pedestrian-level wind speeds

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Abstract

The constant increase in urban populations at the centre of large cities increases the demand for residential developments. Whilst the construction of tall buildings solves many of the housing crises, they introduce several environmental challenges. Accelerating winds at pedestrian level through down-drafting, flow channelling and corner acceleration can cause pedestrian discomfort and in some cases safety concerns. Whilst planning legislations are becoming far more stringent in recent years with the introduction of the City of London Wind Microclimate Guidelines for instance, most architects continue to develop their designs without prior knowledge of aerodynamics. This leads to costly iterative design process involving wind consultants to resolve any issues introduced by the new building massing. However, these investigations are sophisticated and typically conducted in the context of large surrounding environments which cloud our understanding of the fundamental flow features that occur around the individual buildings. This paper examines ten popular angular façade designs in isolation under urban boundary layer conditions and assesses each design using a bespoke performance analysis approach designed to scrutinise these designs based on the windiness at pedestrian-level at three key areas. The research confirms that most angular façades produce adverse wind effects at ground level compared to a standard cuboid building.

Keywords: building performance, wind microclimate, pedestrian-level wind speeds, tall building, angular façades, aerodynamics.

1 Introduction

The City of London faces a challenge of urban densification as the projected urban population is expected to reach 10.2M people in 2030 compared to 7.2M in the beginning of the millennium [1]. This increase along with the limited available land, is one of the primary factors leading developers to construct tall buildings, which introduce several environmental challenges including wind microclimate. Tall buildings tend to cause several wind issues at pedestrian level due to downdraughting high speed winds, channelling winds between proximity buildings and accelerating winds around sharp corners. This influences the comfort of pedestrians using the streets of London for leisure walking and commuting around tall building which is continuously rising [2]. The importance of wind microclimate in London has gained popularity in recent years with the development of 'Wind Microclimate Guidelines" for new developments in the City of London [3].

To date, much of the existing literature has focused on the influence of basic geometrical shapes including varied lift-up buildings [4], parametric studies of various design features, such as permeable floors, podiums, and canopies [5], corner modifications [6], and incremental optimisation of the building form by varying the massing width, length, and height [7] on pedestrian-level wind speeds. Whilst these studies offer useful insights into the influence of building parameters on the pedestrian-level wind speeds, they focused primarily on perpendicular façades (normal to the ground plane). Modern tall building designs often have sophisticated façades such as the Scalpel, the Leadenhall building, the Walkie-talkie, and the Shard in London, UK. These types of angular façades can promote downdraught effects and cause wind accelerations closer to pedestrian-level.

In addition, the effect of corner modifications on pedestrian wind comfort have also been investigated by Zhang et al. [8] and Mittal et al. [9] on a cuboid building. Their research concluded that chamfered or filleted corners reduced wind speeds and improved pedestrian comfort due to the decrease of pressure differentials between adjacent façades. Again, these corner modifications improvements were only verified on perpendicular façades and their effect was not quantified on angular façade geometries.

To advance this body of knowledge, computational fluid dynamics (CFD) was used to examine the impacts of various façades including upward and downward tapered façades, curved façade, folding façade, pyramid shaped façade and ranks the performance of these façades in improving pedestrian-level wind speeds.

2 Methods

2.1 Computational Setup

The simulations were undertaken, using OpenFOAM (v.9) CFD software. Reynolds Averaged Simulation with a turbulent k-ϵ realizable model was used with a SIMPLE algorithm. The computational domain was setup in accordance to the dimensions shown in Figure 1.

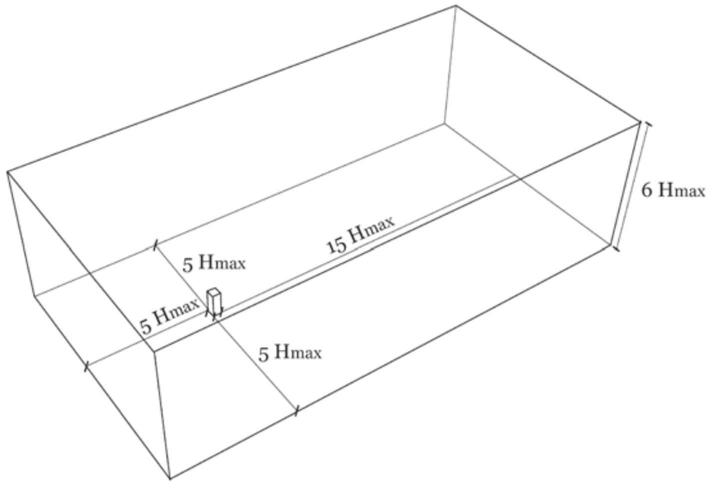
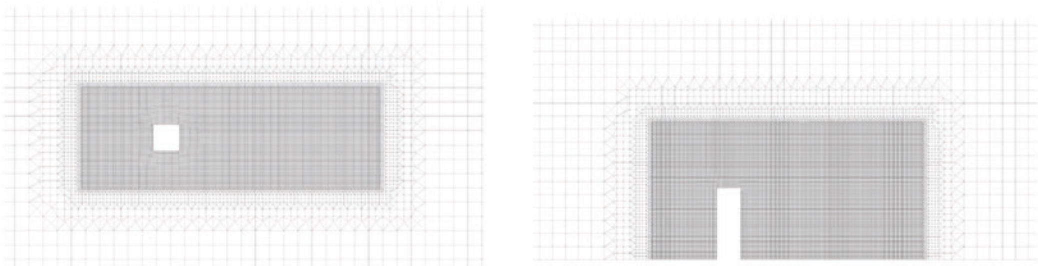


Figure 1: The computational domain

The inlet boundary condition was setup using the atmospheric boundary layer class provided in OpenFOAM [10] and the other boundary conditions were setup as best practice standards for external aerodynamic studies. The grids were setup with 6.6 million cells (Figure 2) and validated against wind tunnel results obtained by Architectural Institute of Japan for Geometry 1 discussed in Section 2.2 [11].



Plan view of grid setup *Section of grid setup*

Figure 2: Structured mesh

2.2 Test Geometries

To examine the effect of angular façades on wind speeds, the length of a building was defined as 'l=33.33m'. All dimensions of the buildings were normalised to 'l' throughout the study. The façade angle (α) was defined as the angle between the approaching wind and building façade. The studied angular facades are shown in Figure 3. To analyse the effect of both angular façades and chamfered corners, the building geometries were setup as shown in Figure 4.

2.3 Performance Analysis Approach

To evaluate the performance of a building geometry in improving wind speeds at 1.5m above the ground plane relative to the baseline (Geometry 1), the velocity contours were divided into three zones – at the building corner, the free shear layer, and wake zone as shown in Figure 5. These areas were selected specifically as most building effects would occur within those regions. Three metrics to assess performance within these zones were defined as the average wind speed, the area of wind that exceeds the average wind speed, and the maximum wind speed. This approach determines which designs provide more favourable wind speeds across each zone. Note that the lower the values obtained the lower the wind speeds.

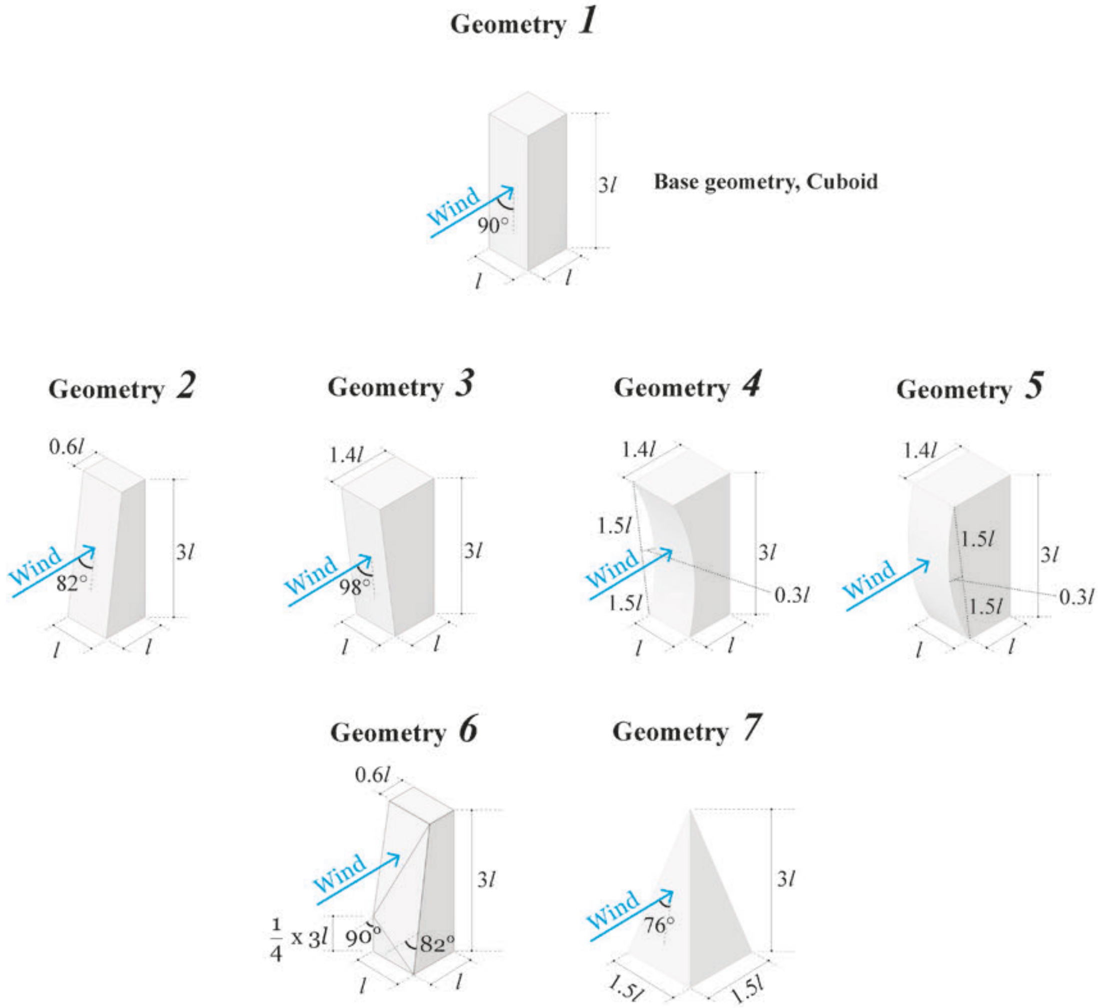


Figure 3: Angular façades

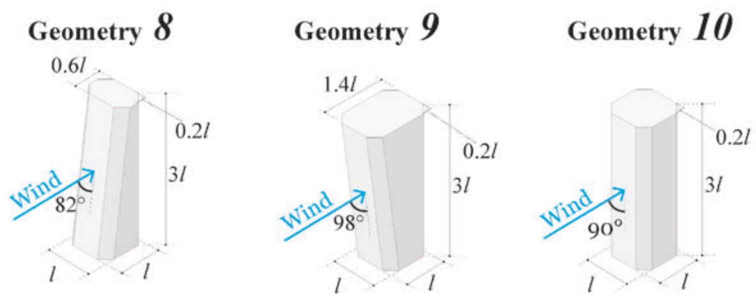


Figure 4: Tapered façades and chamfered corners

However, this is not the case for the area of wind exceeding the average, where a larger area means wind speeds are overall lower. The wind speeds were represented as ratios according to Equation (1):

$$U = \frac{U_0}{U_\infty} \tag{1}$$

U_0 is the local wind speed in m/s and U_∞ is the reference wind speed at free atmosphere wind speed of 10 m/s.

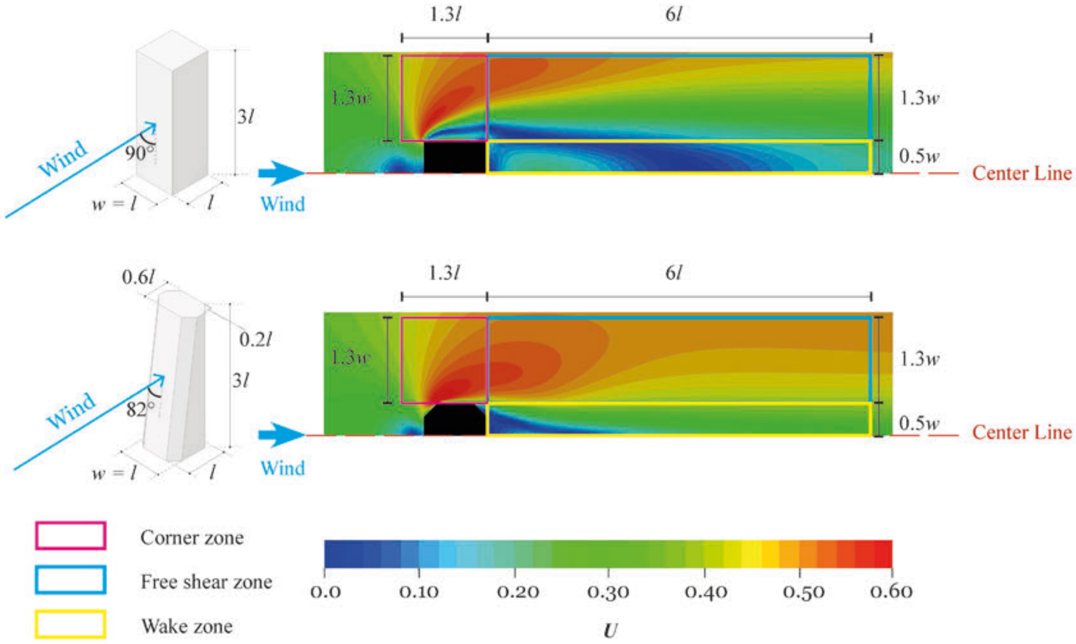


Figure 5: Analysis zones of wind speeds

3 Results

Applying the performance method described in Section 2.3, would produce the results shown in Table 1 for the three zones for each tested geometry. Note that the area above wind speed ratio was calculated as ratio relative to each zone.

The results show that in most cases the average wind speed ratio is highest at the corner, followed by the free-shear layer and the wake zone as expected. This relationship is also true for the maximum wind speed ratio, as the highest accelerations occur at the corner. However, the area above the average wind speed ratio, tends to vary and is largely dependent on the geometry. Whilst these results are insightful and quantify the flow behaviour, they are better understood when compared against each other by taking the average across all three zones as shown in Table 2.

As the average is taken for all three zones for the average wind speed ratio criterion, it becomes clear for instance that Geometry 4 performs similarly to Geometry 1. However, for the other two criteria (i.e. area above the average and maximum wind speed ratios) it tends to be worse. To further advance the performance analysis tool, the results obtained in Table 2 were compared relative to the baseline case (i.e Geometry 1) as a method of normalisation. Taking the average of the normalised values of the three criteria, allows for a ranking system in which façade designs are scrutinised based on their performance in all three zones. Table 3 shows that rank one was the most favourable with the lowest wind speed ratios and rank ten was the windiest with the highest wind speed ratios.

Geometry	Average Wind Speed Ratio			Area above Average Wind Speed Ratio (%)			Maximum Wind Speed Ratio		
	Corner	Free Shear	Wake	Corner	Free Shear	Wake	Corner	Free Shear	Wake
1	0.44	0.36	0.11	72.2	55.4	47.0	0.57	0.54	0.21
2	0.47	0.43	0.15	64.0	60.0	49.5	0.62	0.55	0.28
3	0.42	0.29	0.11	73.2	50.9	51.0	0.58	0.54	0.22
4	0.46	0.36	0.09	63.4	55.4	44.9	0.60	0.54	0.21
5	0.40	0.26	0.12	67.7	50.1	50.5	0.61	0.53	0.22
6	0.47	0.44	0.16	63.8	59.2	48.4	0.62	0.55	0.30
7	0.46	0.46	0.25	58.3	65.4	56.4	0.62	0.52	0.39
8	0.49	0.48	0.28	51.8	55.3	60.7	0.69	0.56	0.42
9	0.45	0.34	0.14	67.7	56.6	55.1	0.55	0.53	0.25
10	0.45	0.40	0.14	66.6	61.8	52.6	0.56	0.54	0.27

Table 1: The average, area above the average and the maximum wind speed ratios for the corner, free shear layer, and wake zones

Geometry	Mean Wind Speed Ratio at the Three Zones		
	Mean Value of Average Wind Speed Ratio at the Three Zones	Mean Value of Area above Average Wind Speed Ratio (%) at the Three Zones	Mean Value of Maximum Wind Speed Ratio at the Three Zones
1	0.30	58.2	0.44
2	0.35	57.8	0.48
3	0.27	58.4	0.45
4	0.30	54.6	0.45
5	0.26	56.1	0.45
6	0.36	57.1	0.49
7	0.39	60.0	0.51
8	0.42	55.9	0.56
9	0.31	59.8	0.44
10	0.33	60.3	0.46

Table 2: Combined mean values of the three criteria across the three zones

In general, it appears as though most angular façades (other than the downward tapered designs) would not yield a calmer wind environment surrounding the building than the standard cuboid building. Although, note that specific design features such as chamfering corners would show improvements in reducing the area above the average and maximum wind speeds in line with previous research of chamfered buildings.

Geometry	Normalised Mean Wind Speed Ratio at the Three Zones			Average of Three Normalised Values	Rank
	Normalised Mean Value of Average Wind Speed Ratio at the Three Zones	Normalised Mean Value of Area above Average Wind Speed Ratio (%) at the Three Zones	Normalised Mean Value of Maximum Wind Speed Ratio at the Three Zones		
1	100.0	100.0	100.0	100.0	3
2	115.4	100.6	109.8	108.6	7
3	90.1	99.7	101.5	97.1	1
4	100.0	106.6	102.3	103.0	5
5	85.7	103.7	103.0	97.5	2
6	117.6	101.8	111.4	110.3	8
7	128.6	96.9	115.9	113.8	9
8	137.4	104.0	126.5	122.6	10
9	102.2	97.3	100.8	100.1	4
10	108.8	96.4	103.8	103.0	6

Table 3: Normalised mean values of average, area above average, maximum wind speed ratios (%) and rank

4 Conclusions and Contributions

This paper presents CFD results examining the effects of tall buildings angular façades on pedestrian-level wind speeds relative to a cuboid building. Due to the large number of designs, a performance analysis approach was developed to scrutinise the buildings based on the level of windiness at three key zones surrounding the buildings. These are the corner zone, the free shear layer zone and the wake zone.

The metrics used to determine whether a building produced higher wind ratios was based on the average wind speed, the area that exceeds the average wind speed and the maximum recorded wind speed for each zone. By combining these metrics through normalisation and further averaging, the tool can assess whether a design produces calmer conditions relative to a baseline design. The summary of the outcomes of this investigation which ranks each design is presented in Table 4.

Rank	Geometry	Average of Three Values: Normalised Mean of Average, Area above Average, and Maximum Wind Speed Ratios	Building Geometry
1	3	97.1	Downward Taper
2	5	97.5	Downward Taper, Convex
3	1	100.0	Cuboid
4	9	100.1	Downward Taper, Chamfer
5	4	103.0	Downward Taper, Concave
6	10	103.0	Cuboid, Chamfer
7	2	108.6	Upward Taper
8	6	110.3	Folding Façade, Upward Taper
9	7	113.8	Pyramid
10	8	122.6	Upward Taper, Chamfer

Table 4: Geometry ranking from most favourable wind speeds to least favourable relative to Geometry 1 (i.e. cuboid building)

The results revealed that Geometries 3 and 5 which both had a form of downward tapering reduced the wind speed ratios compared to a cuboid building at pedestrian level. These façade designs appeared to push the fast-moving flows away from the corners abruptly creating a localised area surrounding the building with low wind speeds. On the other hand, Geometry 8 (with an upward taper and corner chamfers) was ranked last with the highest wind speed ratios. This was attributed to the combination of corner chamfers and upward taper façade which created a far windier environment than a cuboid building at pedestrian-level.

These quantifications can guide architects and engineers to understand their designs in a fundamental level in the absence of surrounding environment. However, in reality winds approach from all directions and the scale and number of surrounding buildings can severely influence the results shown here. As such, further research into the influence of those parameters will be discussed in future publications.

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