SKYSCRAPERS ARCHITECTURAL FORM EFFECTS ON AIRFLOW

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ABSTRACT

In today's architectural world, skyscrapers building has been a common typology of building in urban areas despite challenges on its construction, economy feasibility, comfort of occupants and even on its technical aspects like aerodynamic characteristics towards wind. In relation to the air pressure effect on building surfaces due to the mass buildings development, this paper reviews on the varying building forms effects to the wind ventilation circulating the surrounding area. For such building, aerodynamic forces include three modes of action: along wind, across wind and torsional modes. To overcome such challenges, 'Aerodynamic Mitigation' techniques and 'Aerodynamic Shape Optimization' techniques were used. Basic shapes and modified shapes of square prism, cylindrical and pyramidal were tested through wind tunnel using Airflow meter with Pitot tube to determine the aerodynamic characteristics in winds from different directions. The study also shows the significance of aerodynamic modifications as an effective design approach in terms of mitigating wind excitation. The results of these experiments have led to comprehensive understanding of the aerodynamic characteristics of skyscrapers with various configurations. It is proven to an extent that aerodynamic modifications in building shape could moderate wind responses when compared to original building shape. By comparison, cylindrical shows the best aerodynamic performance followed by pyramidal and square prism.

Keywords: *skyscraper, aerodynamic modification*

INTRODUCTION

The advancements in the development of high strength materials, better understanding of structural behaviour coupled with more advanced analytical tools and structural design procedures have led to a new generation of skyscrapers (Amin & Ahuja, 2010). As the height of the building increases, it is more susceptible to vibration caused by wind due to its asymmetric distribution of mass and stiffness, increased flexibility and insufficient inherent damping. This wind-induced motion, in particular across wind response, endangers the dynamic response of tall structures, the performance of cladding and window, and the habitability of occupants (Bandi, *et al*., 2013). The one effective way to minimize wind-induced vibrations of skyscrapers is to focus more on their shapes in the design stage (Bandi, *et al.*, 2013). It is crucial to consider factor of aerodynamic when designing skyscrapers.

Thus, much research on mitigating wind induced excitations of skyscraper has been carried out. This paper is presenting on the study focuses on the effect of shape modification on the wind flow pattern around skyscrapers.

RESEARCH BACKGROUND

Wind is said to be the most ultimate and unpredictable force affecting skyscrapers; causing skyscrapers to bend and sway in the wind. Therefore, such movement which is known as wind drift, ought to be kept within acceptable limits. It is experimented that the wind drift should not exceed the height of the building divided by 500 (Bennet, 1995). Wind loads on buildings increase considerably with the increase in building heights. Generally, the speed of wind increases with height, whereas the wind pressures increase as the square of the wind speed. Therefore, wind effects on a skyscraper are compounded as its height increases.

One of the wind behaviour which dominant is the variation of its speed with height. The wind speed increases following a curved line varying from zero at the ground surface to a maximum at some distance above the ground. The height at which the speed stops to increase is called the gradient height, while the corresponding speed is called the gradient wind speed (Taranath, 1998). Besides, it is indicated that at heights of approximately 366m above ground, surface friction is almost negligible on the wind speed and can be ignored; as such the wind movement is solely dependent on the prevailing seasonal and local wind effects. The boundary layer diagram as above represents how wind speed is affected by different types of terrain. According to Bennet (2007), as the surface roughness and viscosity changes, more turbulence is created, so the wind speed is affected.

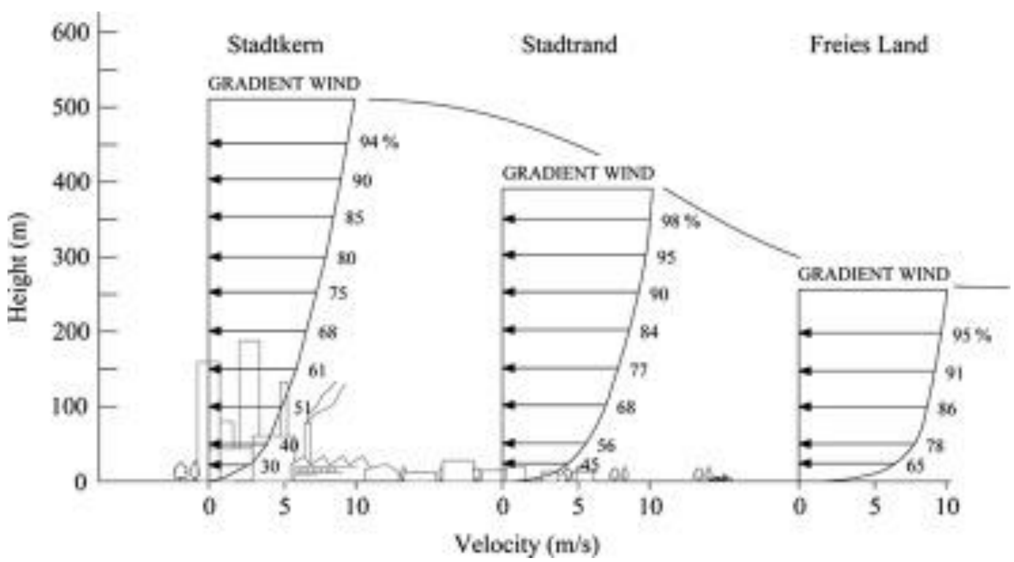


Figure 1: Variation of wind speed with height (Daemei, et al., 2019)

For building such as skyscrapers, aerodynamic forces include three modes of action: along wind, across wind and torsional modes. It is determined by Kareem (1985) that for tall buildings the across wind and torsional response may exceed the along wind response in terms of both serviceability and survivability designs. Skyscrapers are very sensitive to across wind motion, and the sensitivity is apparent as the wind speed increases.

The wind induced motion of a skyscraper can be controlled either by reducing the wind loads or by reducing the response. An appropriate selection of building shape and architectural modifications can result in the reduction of motion by altering the flow pattern around the building. The approaches to reduce wind loads on buildings is to use Aerodynamic Mitigation Techniques or Aerodynamic Shape Optimization Techniques. The various aerodynamic mitigation techniques applied may be classified into two groups which is minor modification and major modification.

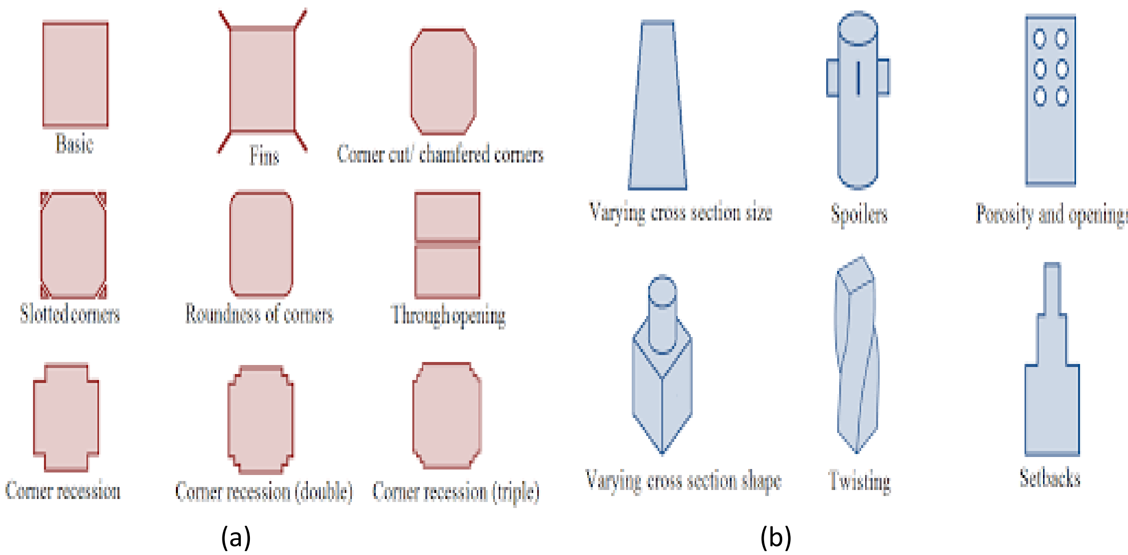


Figure 2: (a) Minor aerodynamic modifications; (b) Major aerodynamic modifications (Power & Jayachandran, 2019)

The ultimate aim of aerodynamic shape optimization is to accurately and efficiently determine surface shapes that attain optimal aerodynamic performance (Power & Jayachandran, 2019). Despite being a static building, aerodynamic elements have successfully proven to lead better impact of wind onto building such as aerodynamic form wind louvres blade and shading devices (Wahab, *et. al*., 2018).

METHODOLOGY

In this research, three different sets of basic shape and modified shape were designed using rapid prototyping. The three basic shapes are square prism, cylindrical and pyramidal; whereas the three modified shapes are duplicate of actual skyscraper which are the Gran Torre Santiago, Marina City Tower and Transamerica Pyramid. Both basic shapes and modified shape were designed to the similar size. Due to limitations of facilities and equipment available, the testing models were designed within the range of 140mm (W) x 140mm (L) x 135mm (H).

By using the scale of 1:2500; the size of Gran Torre model is 20.05mm (W) x 20.05mm (L) x 120mm (H). As for Marina City Towers, it is set to the scale of 1:1500; size of testing model is 29.13mm (W) x 29.13mm (L) x 119.33mm (W). Lastly for Transamerica, the testing model is scaled down to 1:2000; 27.46mm (W) x 27.46mm (L) x 130mm (H).

(a) (b) (c)

Figure 3: (a) Square geometry and duplicated model of Gran Torre Santiago; (b) Cylinder geometry and duplicated model of Marina City Towers; (c) Pyramidal geometry and duplicated model of Transamerica

Based on wind speed data for 14 towns all over Malaysia from the Malaysian Department of Meteorology (1989 to 2008), it is concluded that Malaysia's mean annual wind speed is 1.8 m/s (2 meters above ground). However, towns in the east coast of Peninsular Malaysia such as Mersing, Kota Baharu, and Kuala Terengganu experience stronger winds which exceeded 3 m/s. Hence, the mean wind speed of Malaysia is rounded up to 2 m/s. According to [10], doubling the height of a building increases the wind speed by 10%. Thus, the wind speed of each skyscraper models was determined starting from 2 m/s at 2 meters height above ground.

The wind velocity indicated on the wind tunnel software and the actual wind velocity showed discrepancy. Therefore, manual method of determining wind velocity using Airflow meter with Pitot tube was used instead. Airflow meter with Pitot tube was used to obtain the frequency of wind velocity starting from 1.0 m/s followed by 1.5 m/s, 2.0 m/s, 2.5 m/s until 5.0 m/s.

There are total of 14 traverse points tested for each testing model; each traverse point is distanced 2 cm horizontally and 3 cm vertically. Point 1 and 2 are traverse points to determine wind velocity from z-axis; starting from surface of testing models, followed by 2 cm apart each traverse points (total of 3 traverse points). Wind velocity of each testing models were determined according to its frequency.

(a) (b)

Figure 4: (a) & (b) Determine frequency of wind velocity using Airflow meter with Pitot tube

(a) (b)

Figure 5: (a) Total of 14 traverse points on the cover of testing section; (b) Axis of traverse points

(a) (b)

Figure 6: (a) Set-up of wind tunnel experiment; (b) Placement of testing model in the center of testing section

RESULT AND DISCUSSION

The wind speed input for wind tunnel experiment were analysed beforehand to determine the approximate wind speed to be acted on each testing models. Table 1 shows the increasing wind speed is relative to the point distance from the ground based on the scale used. While it may not giving an accurate speed of increase, the findings reflect earlier research on the real ground (Daemei, et.al., 2019).

Table 1: Relationship between wind speed and distance from ground

Distance from ground (m)	2	4	8	16	32	64	128	256	512
Wind speed (m/s)	2.00	2.20	2.42	2.66	2.93	3.22	3.54	3.89	4.28

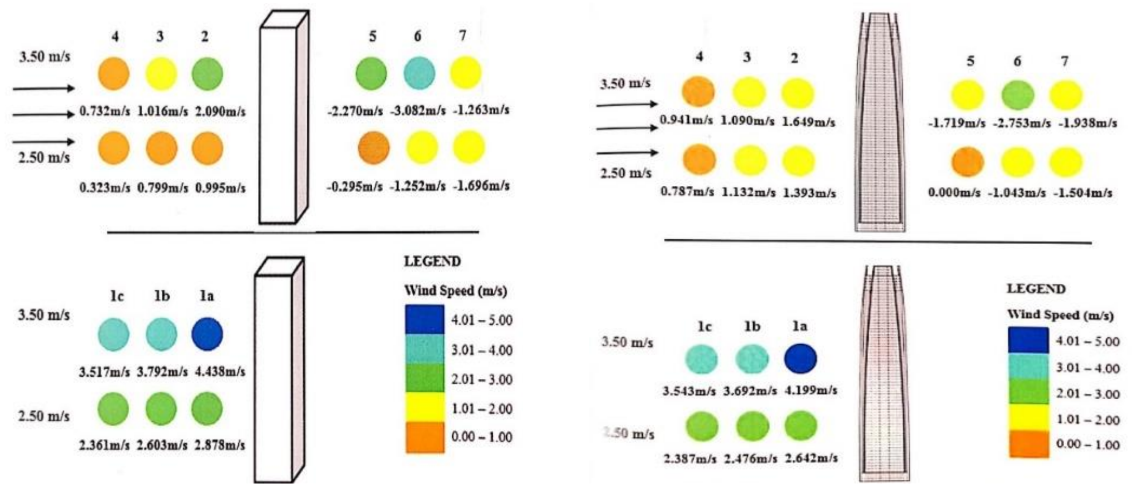
As the research is determining the speed pattern based on the actual speed setting, a trial processes were done in determining the frequency of the wind tunnel in generating the desired speed. The processes are important due to the kind of wind tunnel used for this research do not provided with the wind flow speed setting by the frequency of the propeller. The result is shown in Table 2.

Table 2: Wind speed and frequency used in wind tunnel experiment

Wind Speed (m/s)	**Frequency (Hz)**		
	First Trial	**Second Trial**	**AVERAGE**
1.0	100	100	100
1.5	144	146	145
2.0	193	196	195
2.5	235	235	235
3.0	280	280	280
3.5	320	320	320
4.0	364	366	365
4.5	405	405	405
5.0	445	445	445

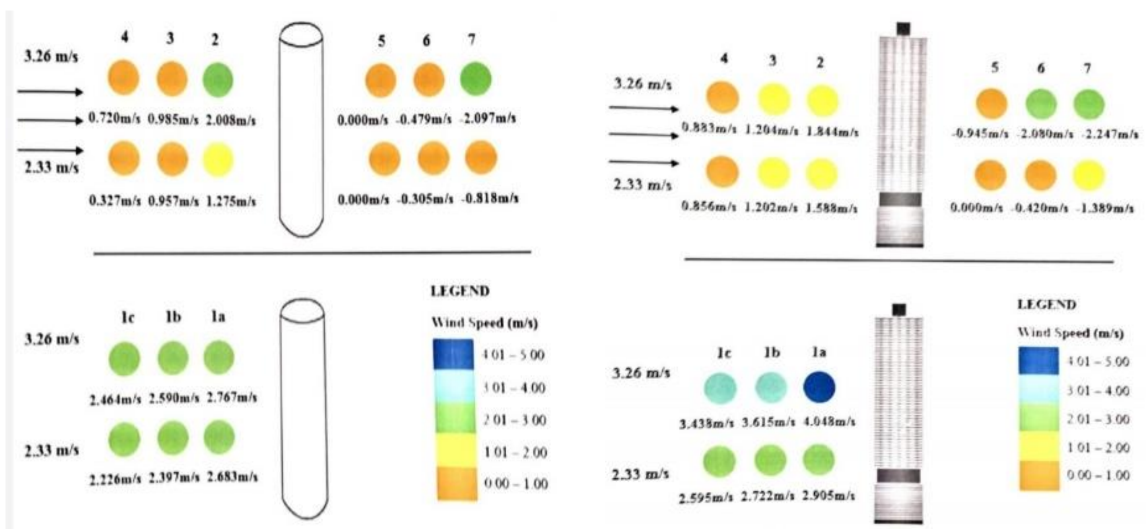
As for the analysis done for the airflow pattern caused by the architectural shape of the skyscraper models, the wind speed is categorised into 5 different colours; orange (0.00 – 1.00m/s), yellow (1.01 – 2.00), green (2.01 – 3.00), light blue (3.01 – 4.00) and dark blue (4.01 – 5.00). The sign of the wind speed indicates the direction of the wind on the surface or element; positive values indicate wind acting towards the surface and negative values indicate wind acting away from the surface (suction). Different shapes to imply different effects to the wind direction. With reference to analysis done for Figure 7 on a square prism model, the formation of the wind flow highlighted different speed level intensity from the windward side to leeward side. Leeward denotes situation where the side is sheltered from the wind. Whilst, windward indicates the direction which aligned to wind. Based on the analysis of the Gran Torre Santiago building, which is slightly tapered on the top form and the comparison done with standard prism form building, the wind direction speed is slightly higher on the leeward side of prism building as compared to the Santiago building form.

However, in terms is side surface wind flow speed direction, both building form exhibit approximately close similar context with one another.



(a) (b)

Figure 7: (a) Wind flow pattern of square prism model; above: wind flow from windward to leeward, below: wind flow from side surface; (b) Wind flow pattern of Gran Torre Santiago model; above: wind flow from windward to leeward, below: wind flow from side surface



(a) (b)

Figure 8: (a) Wind flow pattern of cylindrical model; above: wind flow from windward to leeward, below: wind flow from side surface; (b) Wind flow pattern of Marina City Tower model; above: wind flow from windward to leeward, below: wind flow from side surface

In relation to the building forms comparison in Figure 8, Marina City Tower building is slightly adorned with bigger platform in the base area and intermediate outdoor deck segregating the different platforms. This building is being compared to the normal cylindrical form structure to obtain the leeward-windward and side surface analysis. The Marina-form like structure illustrated a higher wind speed result on the leeward side specifically on the higher level parts of the building as opposed to standard cylindrical form which shows a bit fluctuation at the scale of 7. Besides, Marina-form like structure also exemplify a good result in terms of the side surface analysis for this category of cylindrical shape.

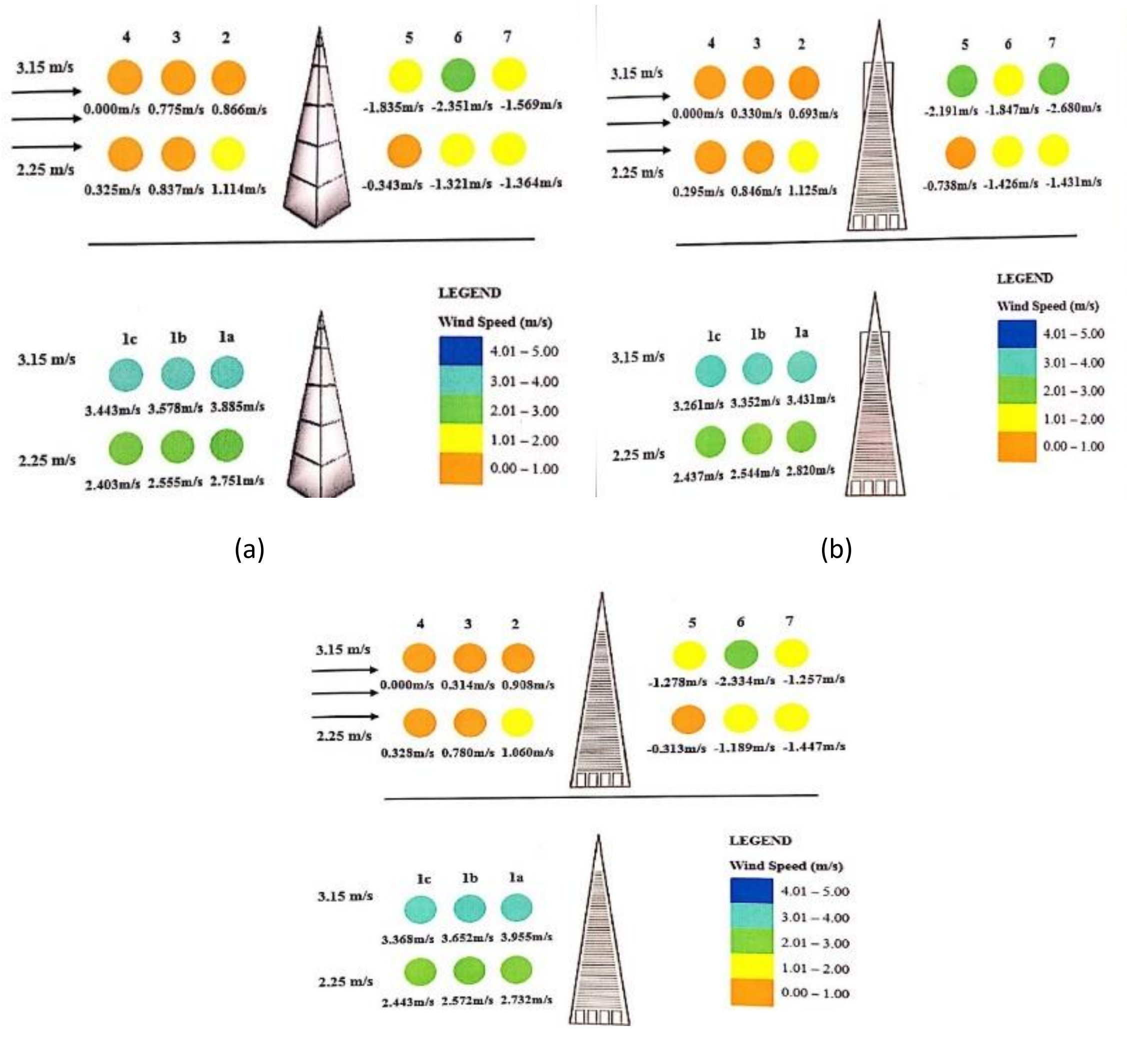


Figure 9: (a) Wind flow pattern of pyramidal model; above: wind flow from windward to leeward, below: wind flow from side surface; (b) Wind flow pattern of Transamerica model (section X); above: wind flow from windward to leeward, below: wind flow from side surface; (c) Wind flow pattern of Transamerica model (section Y); above: wind flow from windward to leeward, below: wind flow from side surface

Figure 9 exhibit the building form analysis effect on the wind direction speed for Transamerica building which is a pyramidal in shape structure with a slight extended platform wings on the top tapered structure. Hence, this particular building is being analyzed for both sides of the sections in comparisons to the standard pyramid form. The Transamerica building for Section X in which with the extended wings tapered top structure illustrated a higher wind speed analysis on the leeward side as compared to Section Y of the building and the standard pyramid form. Nonetheless, in terms of the side surface wind, there of them relatively displayed the same category of load distribution speed.

It is shown that the Gran Torre Santiago model shows better building aerodynamic characteristics compared to square prism model as corner modification helped to reduce the along wind and across wind response on both windward and leeward direction. While the wind flow relationship between cylindrical model and Marina City Tower model shows that basic shape gives more effective aerodynamic characteristics compared modified shape. Such result may due to the surface roughness of Marina City Tower. The modification on the structure surface created turbulence of wind flow and hence increased the wind flow acting on the building surface. As for Transamerica model, it shows better building aerodynamic characteristics compared to Pyramidal model.

CONCLUSSION

Based on the study, it can be concluded that the objectives were achieved. Hence the results and discussion can be summarized as follow:

1. Cylindrical has the best building aerodynamic performance followed by pyramidal and lastly square prism.

2. The modification of edges in Gran Torre Santiago result in reductions in both along wind and across wind responses compared to just basic shape. By modifying the windward corners, it reduced the drag and fluctuating lift forces and hence decrease the wind speed acting on the building surface.

3. Modifications on Marina City Tower showed negative effect compared to basic shape due to its surface roughness which created turbulence of wind and led to increased wind speed.

4. The addition of spoiler help reduce the wind response on Transamerica yet it dependent on the oncoming wind direction. The results indicated that the modification is more effective when the spoiler is perpendicular to the wind direction.

5. It is proven that aerodynamic modification improved building aerodynamic characteristics and act as an effective design approach in term of mitigating wind excitation.

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