ARCHITECTURAL RESPONSE TO EFFECTS OF WIND ON HIGH RISE BUILDING FORMS IN THE DESIGN OF MIXED-USE AT EKO ATLANTIC CITY LAGOS

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Declaration

I declare that the work in this theses entitled “ARCHITECTURAL RESPONSE TO EFFECTS OF WIND ON HIGH RISE BUILDING FORMS IN THE DESIGN OF MIXED-USE AT EKO ATLANTIC CITY LAGOS." has been carried out by me in the Department of Architecture, A.B.U. Zaria. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this project dissertation was previously presented for another degree or diploma at any university.

Abdullahi Muhammad Ahmad	----------	----------
Name of student	Signature	Date

Certification

This project theses entitled "ARCHITECTURAL RESPONSE TO EFFECTS OF WIND ON HIGH RISE BUILDING FORMS IN THE DESIGN OF MIXED-USE AT EKO ATLANTIC CITY LAGOS'' by ABDULLAHI MUHAMMAD AHMAD meets the regulations governing the award of the degree of Master of Science of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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Acknowledgement

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And Protection throughout my life.

Abstract

For decades tall and sealed buildings suffer from the effects of wind, some of which affects ventilation and some affects the structural integrity of the building, effects arising from ventilation leads to high energy consumption through the use of machineries to cool down the building, whereas effects leading to structural failure can arise due to aerodynamic form of the building or adverse environmental conditions

To respond to this problem, different high rise building forms were modelled and simulated to find the one with higher resistance to wind effects, however Lancet form appeared to be the best among the ones chosen with a drag coefficient of -0.15, pedestrian wind speed of 35.6m/s and wind loading of 247pa. To minimize this effects a special ventilation shaft was designed and attached to the Lancet form and re-simulated again, the result from the simulation proved to be workable and interestingly the waste air leaving the ventilation shaft was recorded to have a speed range of 32 -36m/s, and thus this the range required for the operation of wind turbines which was eventually used as an alternative source of power. To verify the workability of this shaft, a physical detail model was prepared and tested, the result from the model was also positive. Therefore, it was concluded that effects of wind resulting to ventilation problems can be avoided through design, and it is recommended that more researches to be carried out to find out more alternative ways of avoiding this problems. However, effects of wind affecting the structural integrity of the building can be minimized through aerodynamic modification to the building form.

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1.0 INTRODUCTION

1.1 Background of Study

For decades, high rise buildings have suffered from the effects of wind because of their height and their aerodynamic forms, the effects varies from location to another due to changes in environmental conditions. However some of this effects could be mild whereas some are dangerous, the mild ones can be eliminated through the introduction of some architectural details to the building form and some through aerodynamic modification to the building form, (Alaghmandan, Elnimeiri, & Bahrami, 2014). But the most common and important problem from the architectural point of view is ventilation, because at higher altitude high wind velocity occur which makes it too dangerous to have an openable window, (Ayşin & Görkem , 2014)

Due to the rapid development in technology, high rise buildings become taller and taller with time, because of their height, the buildings have to be totally sealed to protect them from the adverse effect of wind (Ayşin & Görkem , 2014). However, sealing off these buildings means that, an alternative source of ventilation has to be introduced, which stand as the basis of this research. The alternative means employed was the use of mechanical cooling and air conditioning systems, this system consumes a lot of electricity which makes the operation of this buildings extremely expensive. One major adverse effect of the fully air conditioned and sealed buildings that drew attention was the sick building syndrome, which was a result of humidity and growth of mold through the air-conditioning devices and ducts (Ayşin & Görkem , 2014).

Furthermore; it is observed that, the site selected for this research experiences this effects of wind. Over the years, violent wind storms have attacked Lagos on several occasions

leaving a lot of casualties behind as sourced from local news, reported by Ochereome on Monday, February 13, 2012. Reports of devastation were received from places such as Ebute Metta, Surulere, Sabo, Victoria Island, and the likes. In recent years the maximum sustained wind speed in Lagos main land has reached 111 km/h which is very close to hurricane 1 wind speed.

1.2 Problem Statement

For decades tall and sealed buildings suffer from the effects of wind, some of which affects ventilation and some affects the structural integrity of the building. Effects arising from ventilation leads to high energy consumption and high operational cost by using mechanical cooling system to cool down these buildings, However, Architects are now moving towards passive solution to these problems, Architects like Foster and partners contributed to this research area but however the need for more alternative solutions keep rising as a challenge to young architects. Effects leading to structural failure can arise due to aerodynamic form of the building or adverse environmental conditions which are easier to solve.

1.3 Justification of the Study

This study is necessary in order to improve the indoor air quality in sealed high rise buildings through passive and natural ventilation means, and also to cut down the operational cost of these buildings by reducing their energy consumption and reliance on mechanical and air conditioning systems while avoiding sick building syndrome.

1.4 Aim

The aim of this research is to draw a distinction or hierarchy in basic high rise building forms in order of effects they receive from high wind speed and how this wind effects can be minimized through design.

1.5 Objectives

i. To identify different high rise building forms

ii. To simulate the identified building forms under wind scenario and study how the building forms respond to the wind effects

iii. To conduct a comparative analysis of the different building forms with the goal of identifying the best to be used for this research.

1.6 Delimitation of the Study

The study is limited to effects of wind on high rise building forms with a maximum number 65 floors at Eko Atlantic City, Lagos.

2.0 LITERATURE REVIEW

2.1 Introduction

Judging from the 21st century skyscrapers of nowadays, it is obvious that the future or the next generation of skyscraper buildings forms will be more towards aerodynamic and curvilinear shapes and forms. Considering the effect of the wind on tall buildings forms, according to (Alaghmandan, Elnimeiri, & Bahrami, 2014) two important facts are worth mentioning to confirm the reason of this expected trend. Firstly, aerodynamic building forms can reduce the effect of wind on tall buildings. This fact shows the importance of the effect of the form and geometry of the buildings designed by architects. Hence, in many of the most famous tall buildings, these aerodynamically favorable forms are preferred and the effectiveness of them is significant. For instance, in Taipei 101 corner modifications provide 25% reduction in the base moment when compared to the original square section (Alaghmandan, Elnimeiri, & Bahrami, 2014). Secondly, confusing the wind is a very effective solution to reduce the wind effect. Aerodynamic forms act rather unexpectedly in response to wind, and in general reduce the wind response as well as the across wind effect by confusing wind particularly in vortex-shedding areas. To have a better illustration on such unexpected behavior, it is necessary to explain that irregular aerodynamic forms can disperse the wind and avoid gathering wind flow, which may have a significant integrated effect on the structure of tall buildings. Therefore, such forms can be advantageous in reducing wind load effects and controlling the building responses.

2.2 High Rise Building

The definition of high rise or Tall buildings have changed over time depending on the technology and context. According to the Council on Tall Buildings and Urban Habitat (CTBUH), they define tall and super tall buildings based on height, construction type and

technology. A building is called tall or high rise building when it goes beyond 35 meters or above 12 floors, while super tall are those with heights taller than 300 meters.

2.3 Building Forms Based on Plan

One of the most important architectural factor representing the geometry and form of a tall building is its base plan shape. The figure 2.1 below show the commonly used geometrical shapes are: rectangle, square, ellipse, circle, curvilinear, triangle, polygon and parallelogram. Other forms are a combination of the shapes mentioned (Alaghmandan, Elnimeiri, & Bahrami, 2014)

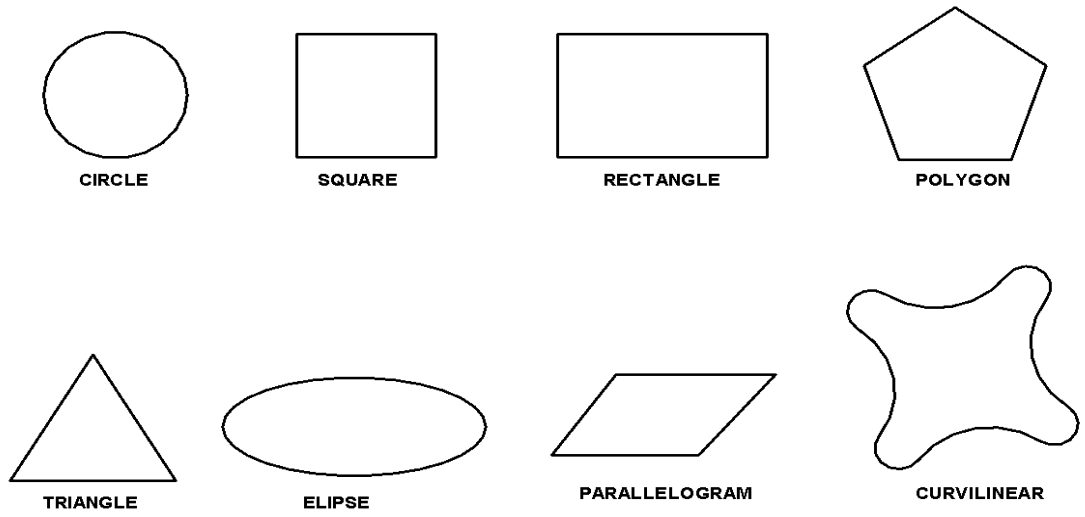


Figure 2.1 Different building forms

(Source: Authors sketch, 2016)

2.4 Building Forms Based on Aerodynamics and Geometry

Due to effects of building form on airflow, different types of the aerodynamic or geometric modifications are considered. The strategy for geometric modification is basically considered as a precautionary and passive architectural concept to reduce the impact of wind as shown in figure 2.2 and 2.3. As sited in (Alaghmandan, Elnimeiri, & Bahrami, 2014) the aerodynamic modifications can be divided into two main categories:

macro and micro. Macro modifications, such as tapering, setback and twisting, they have the basic effect on the main geometry of the building whereas, micro modifications, such as corner modifications, cannot affect the base form and shape of the building.

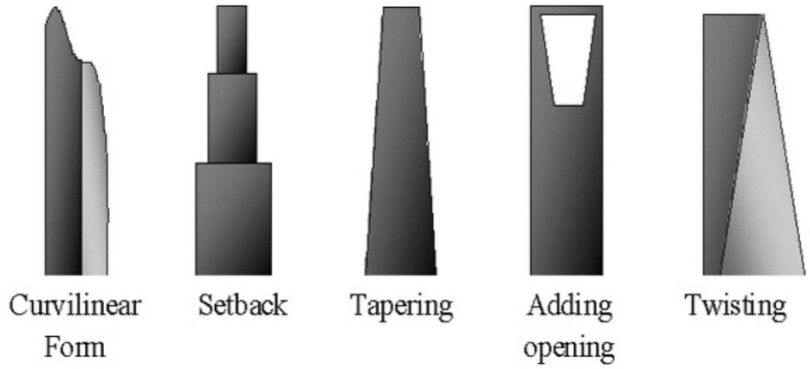


Figure 2.2 macro modification

(Source: Alaghmandan, Elnimeiri, & Bahrami, 2014)

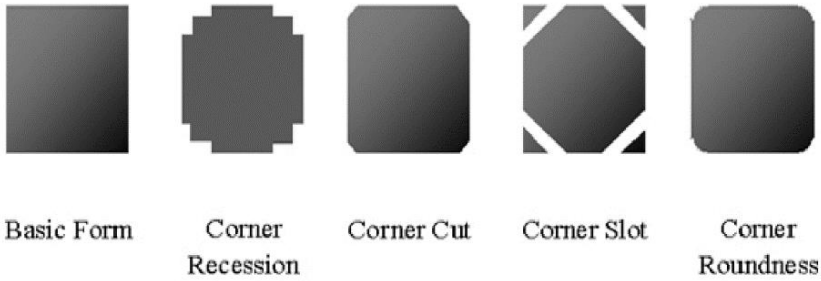


Figure 2.3 Micro modification

(Source: Alaghmandan, Elnimeiri, & Bahrami, 2014)

2.5 Natural Ventilation

Natural ventilation is the process of supplying fresh air and removing it through an indoor space without using any mechanical devices in order to dilute and exhaust pollutants

2.5.1 Natural ventilation principles and strategies for high rise buildings

Generally speaking, the physical mechanisms for natural ventilation in a tall building are the same with ordinary buildings, relying on pressure differences generated across the envelope openings (Ayşin & Görkem , 2014). The pressure differences are generated by:

i. The effects of wind;
ii. Temperature differences that also cause differences in air density;
iii. Combination of both.

Natural ventilation can be classified into wind driven and buoyancy driven (stack effect) as shown in the figure 2.4 below.

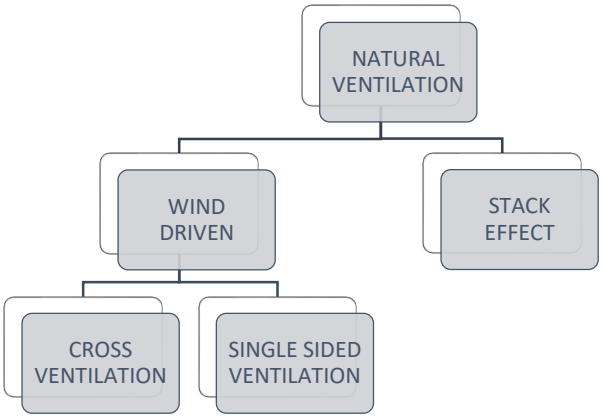


Figure 2.4 Ventilation diagram

(Source: author's diagram 2016)

Wind driven ventilation can be classified in to cross ventilation and single- sided ventilation, and depends on wind behavior, on the interactions with the building envelope and on openings or other air exchange devices such as inlets or chimneys. Some of the important limitations of wind-driven ventilation can be stated as;

i. Unpredictability and difficulties in harnessing due to speed and direction variations,

ii. The quality of air it introduces in buildings may be polluted, for example due to proximity to an urban or industrial area,

iii. May create a strong draught, discomfort.

2.5.2 Cross ventilation

This occurs, where there is a pressure differential between the two sides of a building's envelope involving openings as shown in figure 2.5. In this case the air moves from the windward to the leeward side of the building (Oluigbo, 2014).

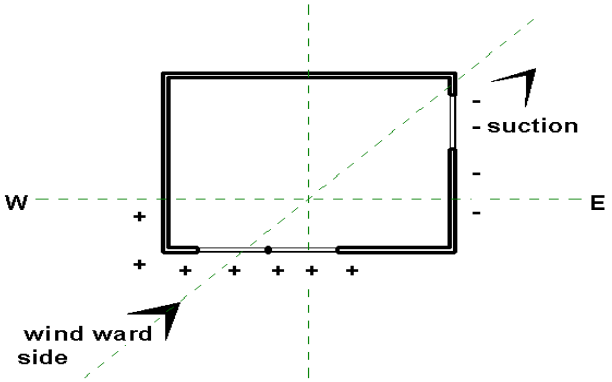


Figure 2.5 Cross ventilation

(Source: Authors sketch, 2016)

2.5.3 Single sided ventilation

This occurs, where fresh air is taken in, and exhausted from the space through the same opening as shown in figure 2.6. In order for this strategy to work, the depth of the space must be a maximum of 2 times its actual height (Ayşin & Görkem , 2014)

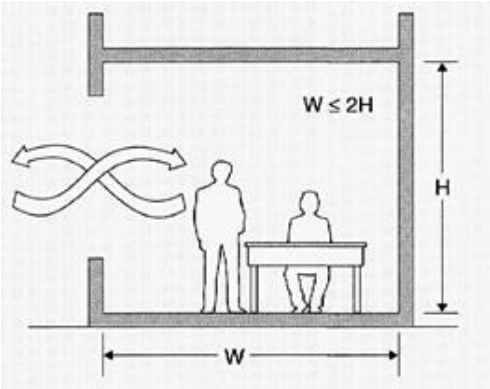


Figure 2.6 Single sided ventilation

Source: (Ayşin & Görkem , 2014)

2.5.4 Stack effect

This occurs where there is a temperature or pressure difference between the exterior and interior of a particular space, it is based on the principle of warm air been replaced by a cooler air (Oluigbo, 2014). The figure 2.7 below show the example of stack effect.

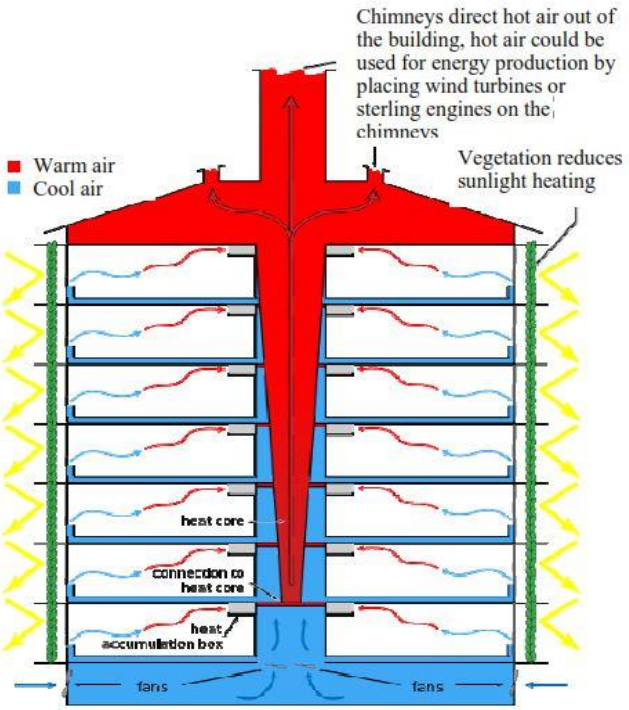


Figure 2.7 Stack effect

(Source: Ayşin & Görkem , 2014)

Benefits of stack ventilation

i. Does not rely on wind, and can take place on hot summer days when it is most needed;
ii. Stable air flow (compared to wind) can be obtained;
iii. Greater control in choosing areas of where air intake can be provided;

Limitations of buoyancy-driven ventilation can also be stated as follows:

i. Lower magnitude compared to wind ventilation on the windiest days
ii. Relies on temperature differences (inside/outside)
iii. Design restrictions (height, location of apertures) and may incur extra costs (ventilator stacks, taller spaces)
iv. The quality of air it introduces in buildings may be polluted for example due to proximity to an urban or industrial area (although this can also be a factor in wind- driven ventilation)

2.6 The Basics of Wind

According to (Bennet, Kepka, Wang, & Watt, 2007) wind is a natural phenomenon that is everywhere and cannot be stopped. However, its effects on building forms can be minimized through design. This section will give an overview of some of the main keywords, and basics of aerodynamic principles that are important in designing for the wind.

2.6.1 Keywords for Building Aerodynamics

Porosity: How well the wind is able to pass through a surface.

Prevailing wind direction: The most common wind direction experienced at the particular location

Surface Roughness: Wind will not travel as smoothly through the urban environment compared to the rural environment because it has a rougher surface to travel across or through.

Turbulence: Instability in the wind causing gusty air currents

Viscosity: How well the wind is able to flow

Windward Face: The building face that comes into contact with the wind first

Gust: A gust is a short, strong, sudden rush of wind

2.7 Air Flow and Wind

According to (Mendis, Ngo, Haritos, Samali, & Cheung, 2007) Wind is a phenomenon of great complexity because of the many flow situations arising from the interaction of wind with structures. Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth's surface. These eddies give wind its gusty or turbulent character as shown in figure 2.8. The gustiness of strong winds in the lower levels of the atmosphere largely arises from interaction with surface features.

The average wind speed over a time period of ten minutes or more, tends to increase with height, while the gustiness tends to decrease with height (Mendis, Ngo, Haritos, Samali, & Cheung, 2007). Therefore, dynamic loading on a structure depends on the size of eddies. Large eddies, whose dimensions are comparable with the structure, give rise to well correlated pressures as they envelop the structure. On the other hand, small eddies result in pressures on various parts of a structure that become practically uncorrelated with distance of separation (Mendis, Ngo, Haritos, Samali, & Cheung, 2007). Eddies generated around a typical structure are shown in

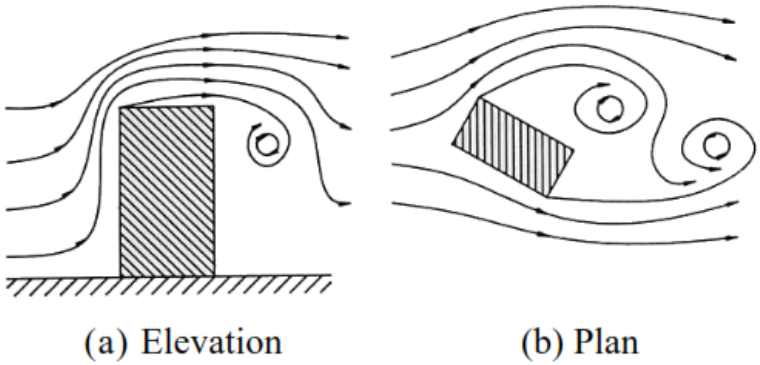


Figure 2.8 Generation of eddies

(Source: Mendis, Ngo, Haritos, Samali, & Cheung, 2007)

2.7.1 Characteristics of wind

Wind speed is the rate at which airflows over time, however wind can come in different categories depending on their speed and the rate of destruction they impact on an object in contact. Wind is classified under different categories by Beaufort as shown in table 2.1a, 2.1b and 2.1c**.** The Beaufort scale is an empirical measure that relates wind speed to observed conditions at sea or on land. Its full name is the Beaufort wind force scale.

Table 2.1a Beaufort scale denoting different wind speed categories on land and on sea

No	Description	Wind speed	Wave height	Sea conditions	Land conditions
0	Calm	< 1 km/h < 0.3 m/s	0 m	Sea like a mirror	Calm. Smoke rises vertically.
1	Light air	1–5 km/h 0.3–1.5 m/s	0–0.2 m	Ripples with the appearance of scales are formed, but without foam crests	Smoke drift indicates wind direction. Leaves and wind vanes are stationary.
2	Light breeze	6–11 km/h 1.6–3.3 m/s	0.2–0.5 m	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break	Wind felt on exposed skin. Leaves rustle. Wind vanes begin to move.

Table 2.1b Beaufort scale denoting different wind speed categories on land and on sea

No	Description	Wind speed	Wave height	Sea conditions	Land conditions
3	Gentle breeze	12–19 km/h 3.4–5.5 m/s	0.5–1 m	Large wavelets. Crests begin to break; scattered whitecaps	Leaves and small twigs constantly moving, light flags extended.
4	Moderate breeze	20–28 km/h 5.5–7.9 m/s	1–2 m	Small waves with breaking crests. Fairly frequent whitecaps.	Dust and loose paper raised. Small branches begin to move.
5	Fresh breeze	29–38 km/h 8–10.7 m/s	2–3 m	Moderate waves of some length. Many whitecaps. Small amounts of spray.	Branches of a moderate size move. Small trees in leaf begin to sway.
6	Strong breeze	38–49 km/h 10.8–13.8 m/s	3–4 m	Long waves begin to form. White foam crests are very frequent. Some airborne spray is present.	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. Empty plastic bins tip over.
7	High wind, moderate gale, near gale	50–61 km/h 13.9–17.1 m/s	4–5.5 m	Sea heaps up. Some foam from breaking waves is blown into streaks along wind direction. Moderate amounts of airborne spray.	Whole trees in motion. Effort needed to walk against the wind.
8	Gale, fresh gale	62–74 km/h 17.2–20.7 m/s	5.5–7.5 m	Moderately high waves with breaking crests forming spindrift. Well-marked streaks of foam are blown along wind direction. Considerable airborne spray.	Some twigs broken from trees. Cars veer on road. Progress on foot is seriously impeded.
9	Strong/severe gale	75–88 km/h 20.8–24.4 m/s	7–10 m	High waves whose crests sometimes roll over.	Some branches break off trees, and some small trees blow over.

Table 2.1c Beaufort scale denoting different wind speed categories on land and on sea

No	Description	Wind speed	Wave height	Sea conditions	Land conditions
10	Storm whole gale	89-102 km/h 24.5–28.4 m/s	9–12.5 m	Very high waves with overhanging crests. Large patches of foam from wave crests give the sea a white appearance. Considerable tumbling of waves with heavy impact. Large amounts of	Trees are broken off or uprooted, structural damage likely.
11	Violent storm	103–117 km/h 28.5–32.6 m/s	11.5–16 m	Exceptionally high waves. Very large patches of foam, driven before the wind, cover much of the sea surface. Very large amounts of airborne spray severely reduce visibility.	Widespread vegetation and structural damage likely.
12	Hurricane force	≥ 118 km/h ≥ 32.7 m/s	≥ 16 m	Huge waves. Sea is completely white with foam and spray. Air is filled with driving spray, greatly reducing visibility	Severe widespread damage to vegetation and structures. Debris and unsecured objects are hurled about.

(Source: Beaufort n.d.)

2.7.2 Wind data for Lagos Mainland.

It is important to relate the wind data of the area of study with the above Beaufort wind scale, to know the categories of wind blowing over the area with time. The chart in Figure 2.9 plots the average daily wind speed you can expect for any month. It also shows the maximum recorded sustained wind speed for each month.

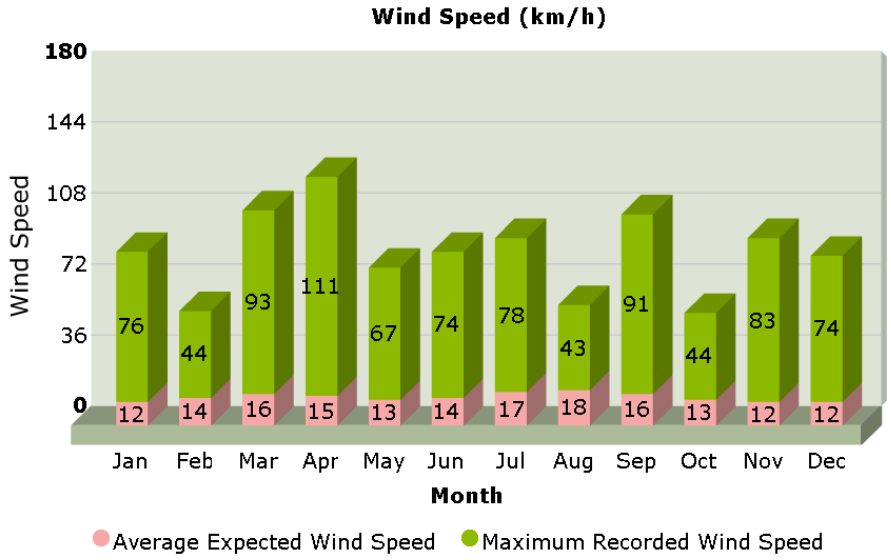


Figure 2.9 Lagos average daily wind speed for any month

It is important to note that the highest wind speed recorded falls on the month of April at a speed of about 111km/h which is equivalent to violent storm category, and the destruction involved structural damage and fallen of glass which may be a threat against the skyscrapers in that location. Most importantly it is necessary to note that the above wind data recorded was for Lagos mainland and the proposed site is the reclaimed land from the Atlantic Ocean, therefore the wind speed in that particular location may vary slightly from that of the mainland. According to davenports classification of aerodynamic roughness, he correlate terrain vs obstructions to arrive at drag coefficient which in another perspective explains how wind blow freely at full speed. See table 2.2a and 2.2b

Table 2.2a The Davenport classification, where z_o is aerodynamic length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

Z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
0.005	Smooth	Beaches, pack ice, morass, snow-covered fields	0.0028
0.03	Open	Grass prairie or farm fields, tundra, airports, heather.	0.0047

Table 2.2b The Davenport classification, where z_o is aerodynamic length and C_{DN} is the corresponding drag coefficient for neutral static stability[b]

Z_0 (m)	Classification	Landscape	C_{DN}
0.1	Roughly open	Cultivated area with low crops and occasional obstacles (single bushes)	0.0075
0.25	Rough	High crop, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards.	0.012
0.5	Very rough	Mixed farm fields and forest clumps, orchards, scattered building	0.018
1.0	Closed	Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.	0.030
≥2	Chaotic	Centers of large towns and cities, irregular forests with scattered clearings.	0.062

(Source: Davenport n.d.)

From Table 2.2a and 2.2b, it is clear that places or sites close to an open field like the sea or Ocean would definitely experience more wind speed blowing than areas that are far from the ocean. Therefore, it is expected that artificial Irelands created from the oceans will have increase in wind velocity higher than the violent storms. Above violent storm categories, are the hurricane class of wind which have dangerous consequences on skyscrapers. A case study of Burj Al Arab with the similar scenario reveals the trauma faced by the design team in overcoming the dangerous effect of wind on the building form.

2.8 Effect of Wind on Individual Skyscraper Building Form.

All buildings create obstacles to wind flows. This causes a positive pressure on the windward face and negative pressure zones on the sides, which in turn causes an increase in wind velocity where the two zones meet (Bennet, Kepka, Wang, & Watt, 2007). Wind environment created around a building depends on a lot of factors that will be discussed below.

Individual buildings are not very common; most of the buildings in the urban environment have more than one surrounding building. The effects that are described below generally occur in isolation, with the effect being different where groups of buildings are concerned.

2.8.1 Down draught effect

Wind forces vary with height but up to a certain altitude. This variation in profile is from ground level to 10m or 15m above the zero level. After that the profile of the wind or the wind intensity remains constant (Doshi, 2013) see plate 2.1.

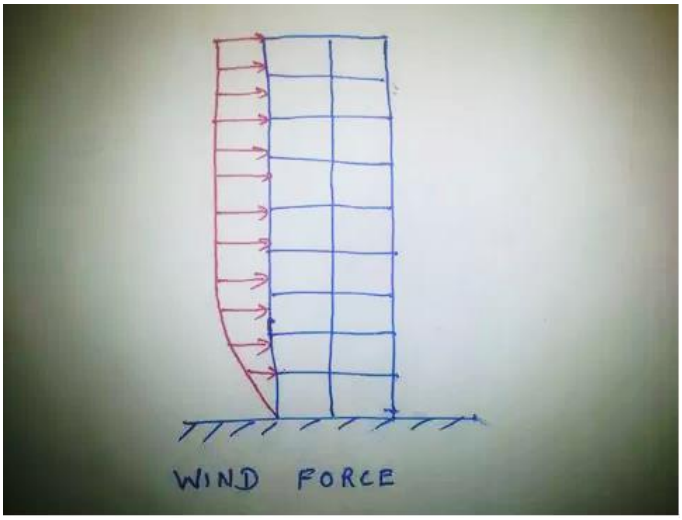


Plate 2.1 Wind profile

(Source: Doshi, 2013)

It is an established fact that speed increases with height, when a tower is exposed to certain wind speeds, the pressure is higher than that at the base. This different in pressure forces the high pressure at the top down the windward face which dramatically increases pedestrian wind speeds as shown in figure 2.10. It naturally follows that the taller the exposed windward is, the higher the pedestrian wind speeds will be (Bennet, Kepka, Wang, & Watt, 2007).

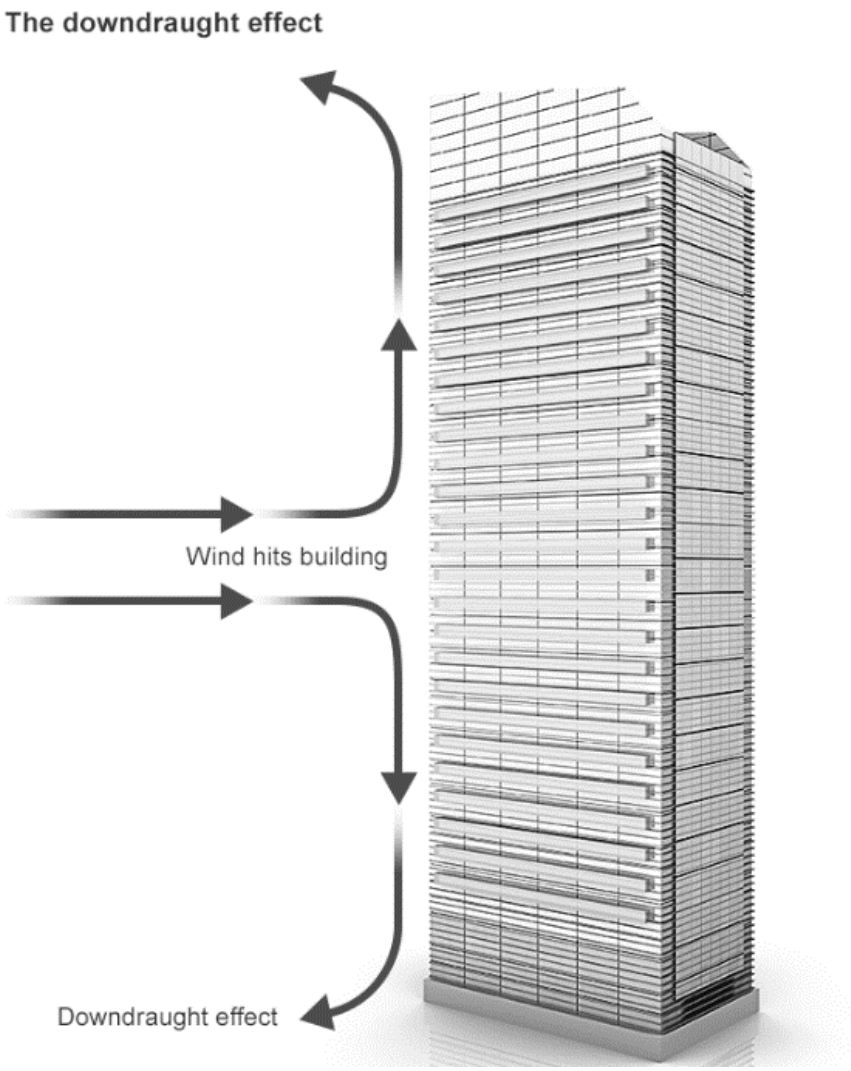


Figure 2.10 Downdraught effect

(Source: Parkinson, 2015)

2.8.2 The corner effect

According to Bernoulli's principles of aerodynamics; at the windward corners of a building, there is always increases in wind speeds. This is due to air being forced around the windward corners from high pressures on the windward face to low pressures in sheltered areas at the sides and rear as shown in figure 2.11 and 2.12. The greatest wind speeds occur within an area of equal distance to the width of the building.

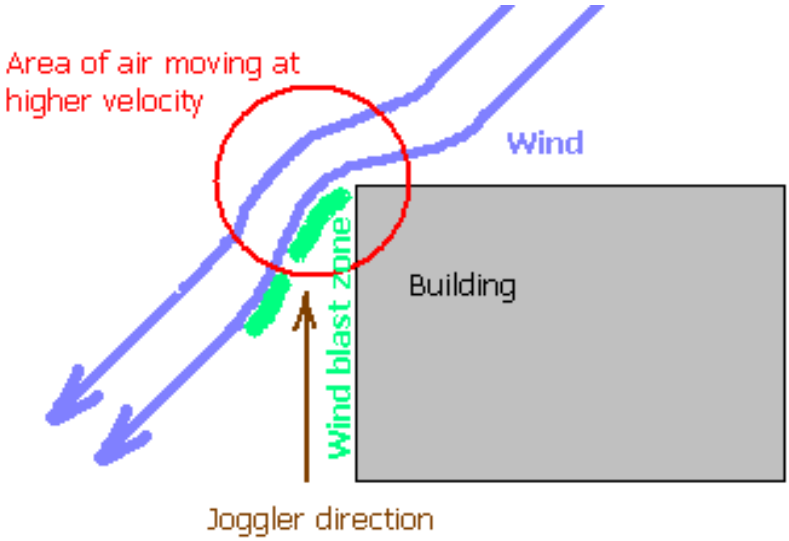


Figure 2.11 Corner effect

(Source: http://www.comfsm.fm/~dleeling/kinesiology/ Bernoulli. Html)

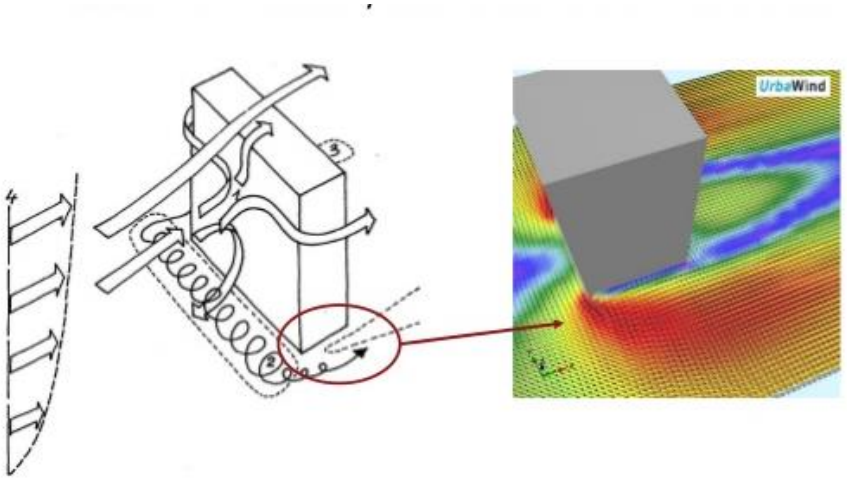


Figure 2.12 Corner effect on simulated model.

(Source: Meteodyn, 2015)

2.8.3 The wake effect

The wake effect is generally caused by downdraught and the corner effect. Increasedwind speeds and turbulence that occurs around the corners of buildings lead to increased pedestrian discomfort due to wind gust at the lower part of the building (Bennet, Kepka, Wang, & Watt, 2007). For example, an isolated 16-storey tower block building causes

about a 40 percent increase in the level of discomfort, whereas a 30-storey building causes a 120 percent increase as shown in figure 2.13 and 2.14 below.

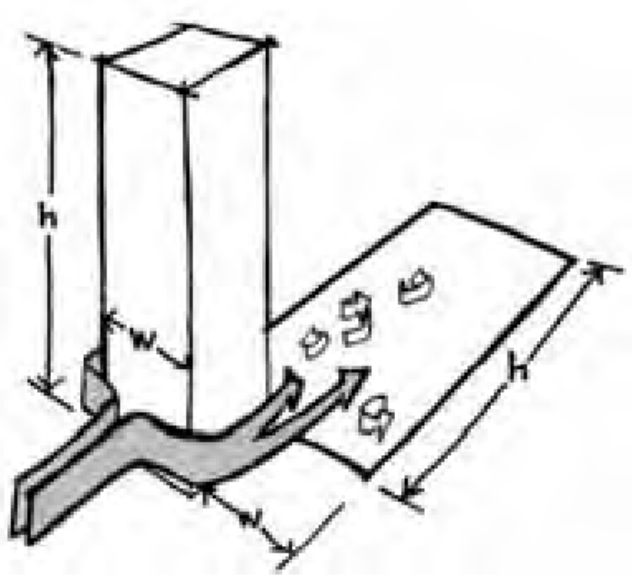


Figure 2.13 wake effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

Each slab block is different in terms of the discomfort it creates and the area of ground it affects. A 16-storey slab block may increase the discomfort level by 60 percent.

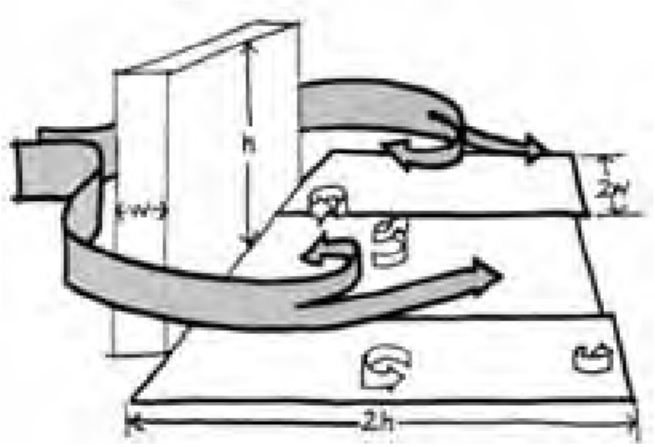


Figure 2.14 Wake effect.

(Source: Bennet, Kepka, Wang, & Watt, 2007)

2.8.4 The low bar row effect

Buildings that have relatively low but wide exposed windward faces cause a wind anomaly called the Row effect. The Bar effect occurs when air flows over a street at a 45-degree angle. On the opposite side (leeward) the wind speeds up as shown in figure 2.15 and 2.16 below. This effect depends on the width, length, and average height of the sides and size of the openings in the street. (Nakamura & Oke, 1988)

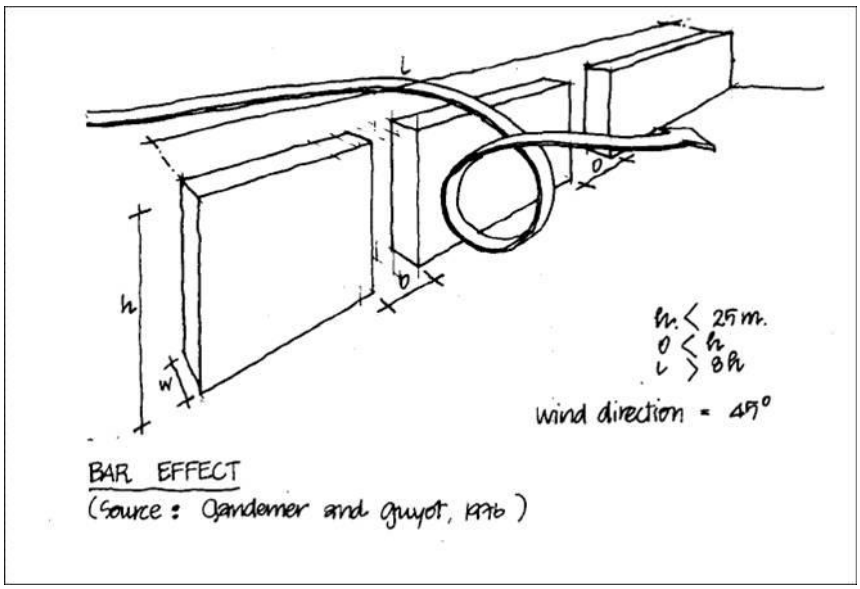


Figure 2.15 Low bar effect

(Source: Nakamura & Oke, 1988)

One way to reduce, or even cancel, the row effect is to add one or several wings to the main block, thus localizing the pedestrian wind level disturbances.

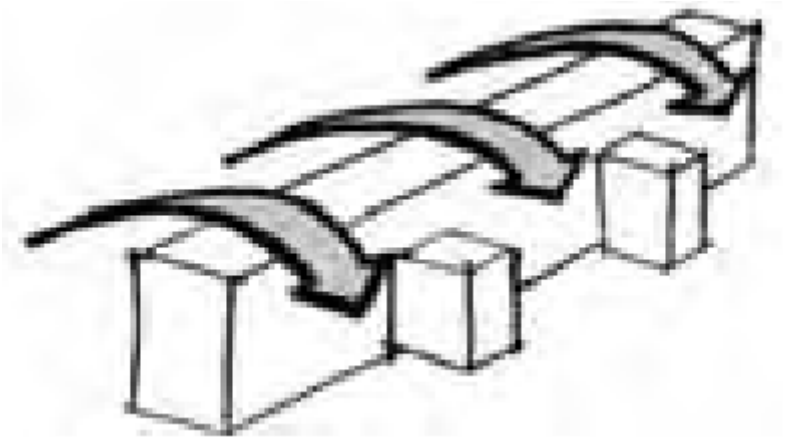


Figure 2.16 Low bar effect.

(Source: Bennet, Kepka, Wang, & Watt, 2007)

2.8.5 Circular building and multi sided buildings

Circular or near-circular Buildings in plan allows the wind to flow freely, inducing relatively little downwards flow. Circular buildings do still induce high wind speeds at the maximum width at right angles to the wind direction (m) as shown in figure 2.17. These wind speeds will be reduced even more if there are relatively low buildings upwind (Bennet, Kepka, Wang, & Watt, 2007).

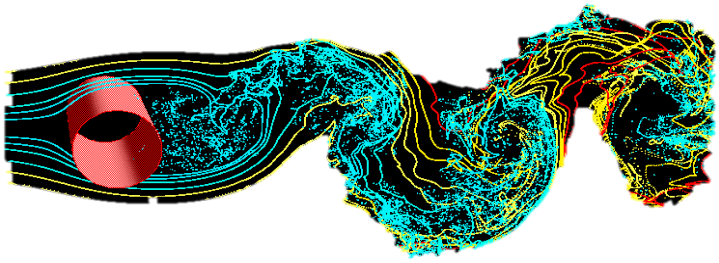


Figure 2.17 Wind flow around a cylindrical building

(Source: Breuer, n.d.)

2.9 Effect of Wind on Grouped Skyscraper Building Form.

The effects experience on an individual building form will be different from the one experienced on a group or cluster arrangement of different high rise buildings as will be explained below.

2.9.1 The cumulative effect

It necessary to note that in reality, there are usually cluster arrangement of buildings and this causes the cumulative wind effect. Cumulative wind effect is when building heights line up so there is a uniform stepping up of building heights so that upward flows add together and increase wind speeds by induction. This also works in the opposite direction, if there is sufficient stepping down then there can be decreases in wind speeds as shown in figure 2.18. Generally the cumulative wind effect is only induced when the dominant building is taller than its surrounding buildings by approximately one third (Bennet, Kepka, Wang, & Watt, 2007).

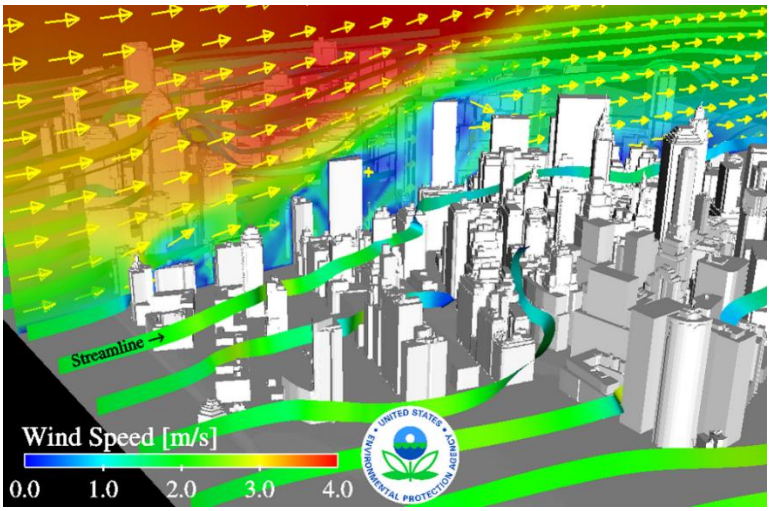


Figure 2.18 Cumulative air flow.

(Source: http://gallery.ensight.com/Images/Aric-images/Created-by-Aric/i-pHcPBhT)

2.9.2 Low and high buildings

Where there are situations of taller buildings and shorter buildings, the combined row and downwash effects can cause extremely high discomfort levels see figure 2.19. And this may cause 100% wake.

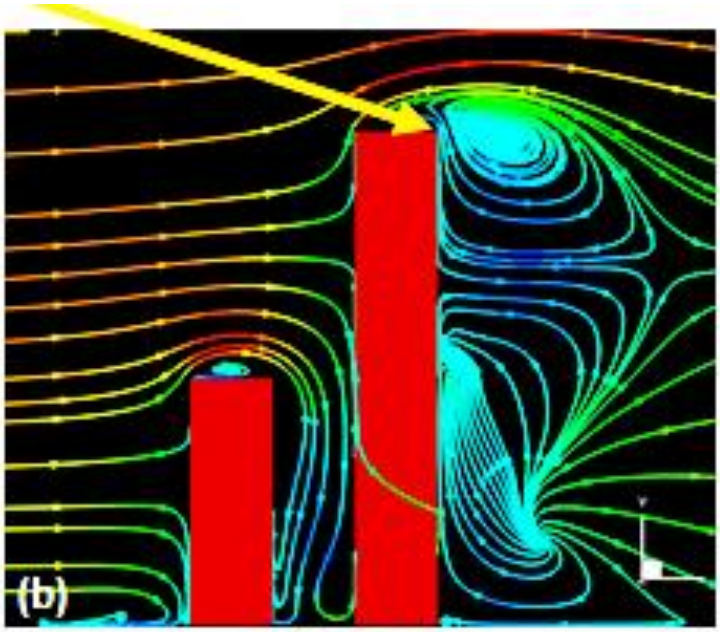


Figure 2.19 low and high effect

(Source: Kyle & Agerneh , 2013)

2.9.3 Staggered buildings

Staggered buildings can do one of two things depending on wind direction and size etcetera. They may protect each other or make the wind environment worse. The latter is due to an increased wind pressure at the unsheltered area (+ side in diagrams) and decreased wind pressure at the sheltered areas (-side in the diagrams). This causes wind to rush from high to low pressure areas. In terms of increases in discomfort levels, the staggering effect is particularly bad. This is because there is no relative increase due to widths, heights and so on as shown in figure 2.20 and 2.21 below. Every situation is

different and discomfort levels differ vastly depending on scale and separation of buildings. (Bennet, Kepka, Wang, & Watt, 2007)

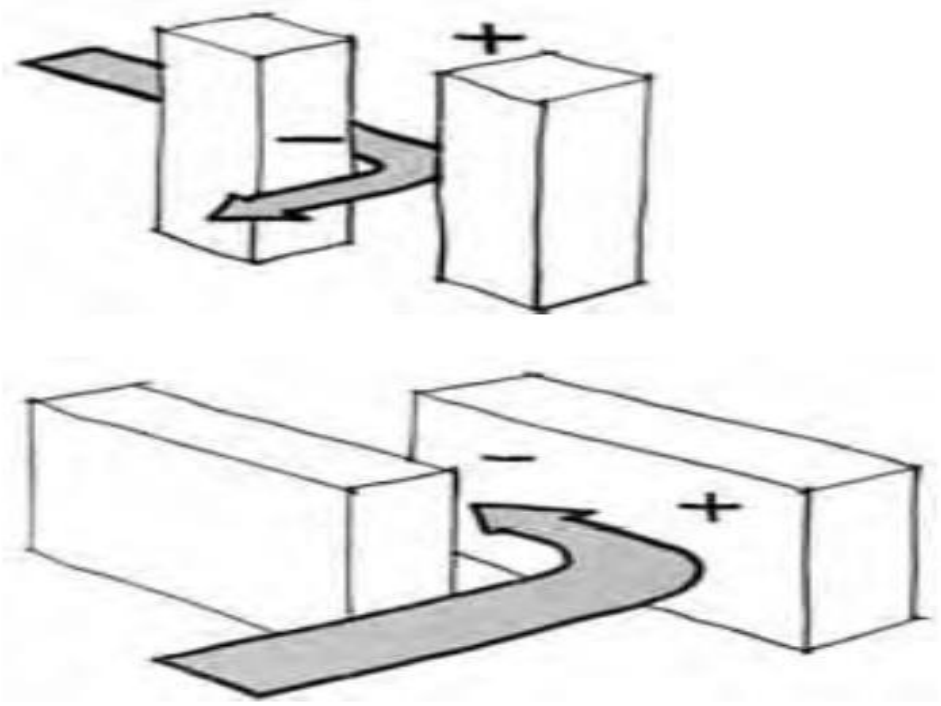


Figure 2.20 Staggered effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

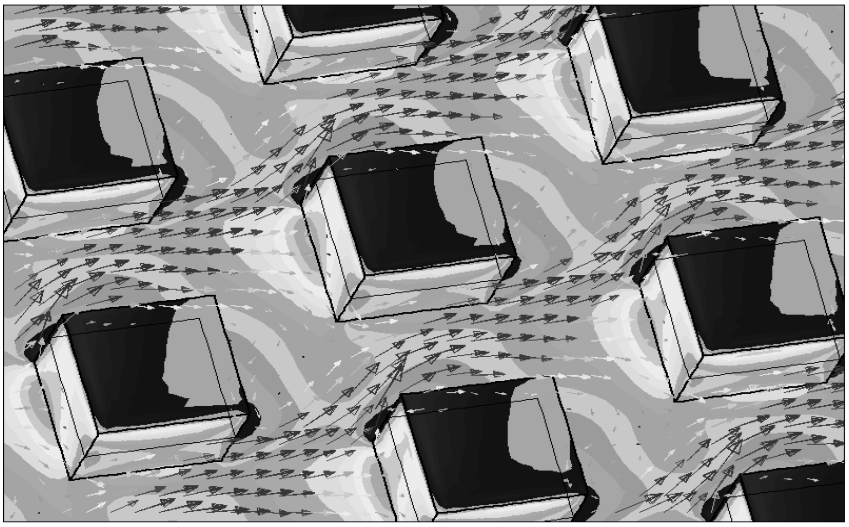


Figure 2.21 Stagger effect worsening condition

(Source: Jean & zheng, 2011)

2.9.4 Channeling effect

The channeling effect occurs when the wind is moving parallel to the street orientation like a corridor. The harshness of this effect is primarily a function of the wind's speed and the total length, the average width, and the average height of the streets corridor as shown in figure 2.22 and 2.23 below. But this can cause discomfort when it receives some other adverse wind conditions and transmits them for the whole length of the corridor. (Nakamura & Oke, 1988).

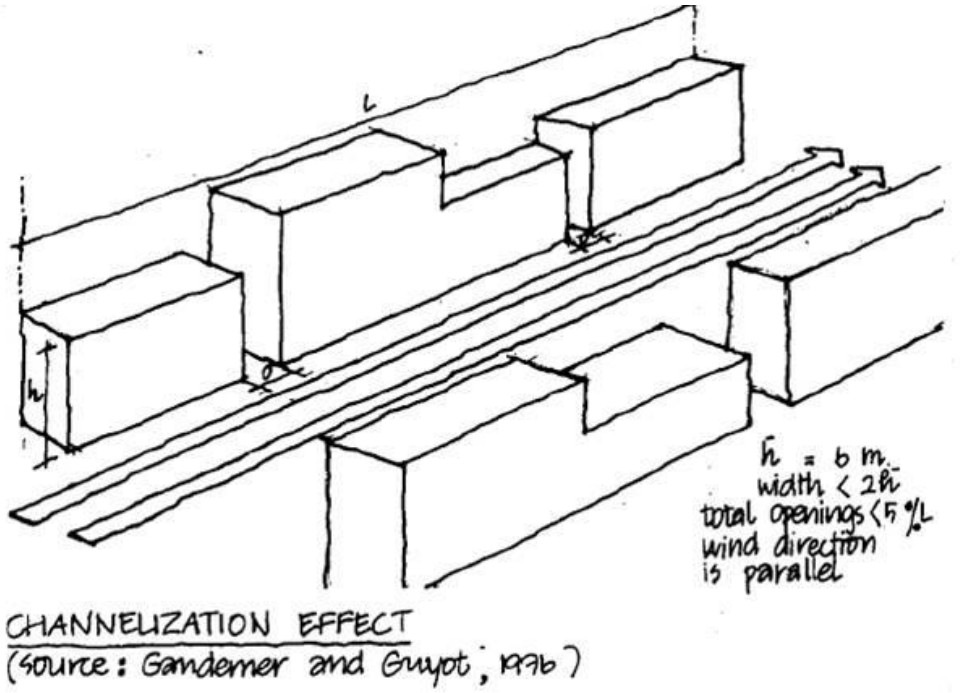


Figure 2.22 channeling effect through corridor

Source: (Nakamura & Oke, 1988)

According to Venturi's effect the speed of wind increases when it funnels through small openings. This is again uncomfortable for pedestrians, but an excellent way to disperse pollutants. The severity of the Venturi effect is a function of width, length, height, and size of openings in the corridor.

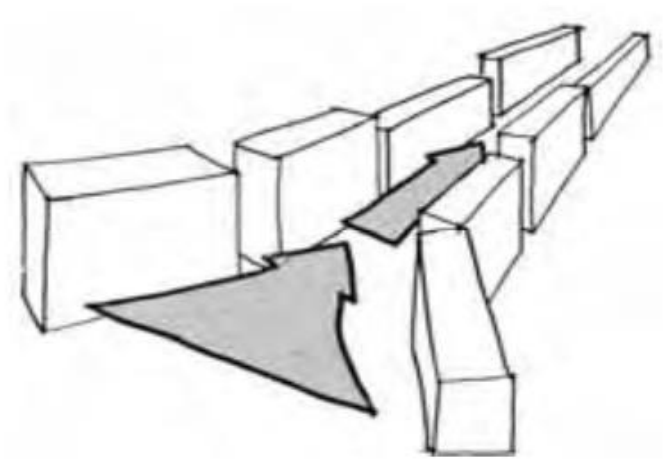


Figure 2.23 Venturis effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

2.9.5 Funneling effect

This phenomenon is formed when structures are arranged in funnel like shape with a narrow ending and wider opening as shown in figure 2.24 and 2.25 below. The critical zone for comfort is at the neck. Adverse funneling effects occur when the relevant buildings are more than five stories high, or more than 100 meters long, and the upstream and downstream funnels are clear of obstructions. (Bennet, Kepka, Wang, & Watt, 2007).

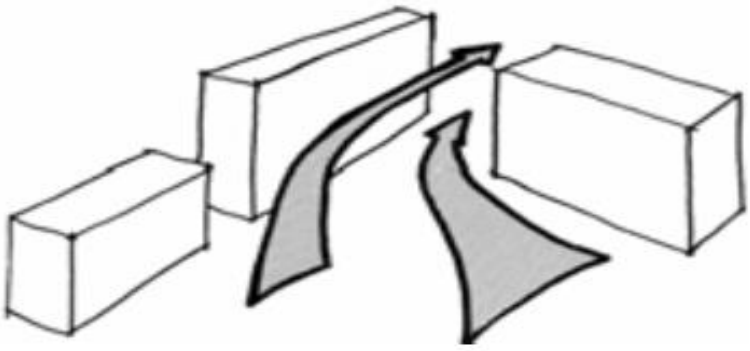


Figure 2.24 Funneling effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

There would be a greater adverse wind reaction where the Venturi effect applies. If, after the bottleneck, the rows of buildings diverge, then an aerodynamic nozzle is formed. In this situation, building heights of about five stories could cause a 100 percent increase in discomfort level. If one or more of the buildings forming the acute angle is also curved in plan, a more aerodynamic situation is created and the wind problem is increased.

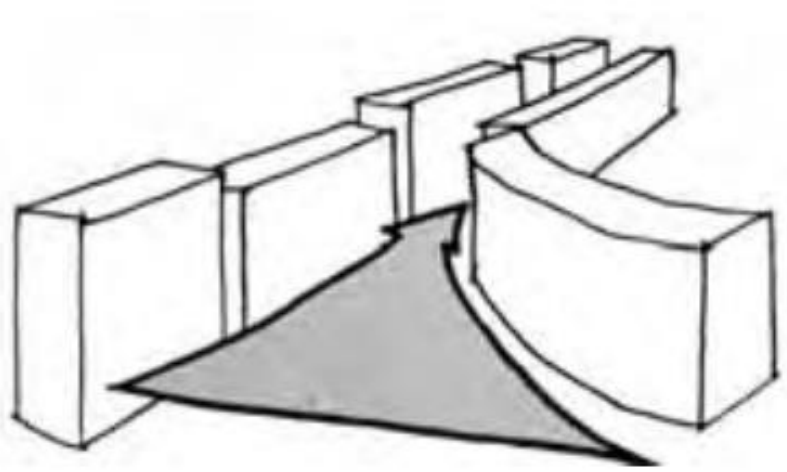


Figure 2.25 Funneling effect/Venturi effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

2.9.6 Tower and podium effect

When outdoor air flows by a high-rise building, a flow separation occurs at a certain height of the building facade. Part of the airflow crosses upward over the building; some part moves toward both sides; and another large part of the flow moves downward and forms a downwash flow, and a horseshoe vortex is subsequently generated at the bottom of the upwind side, moving toward both sides of the corner as shown in figure 2.26. This vortex and another wind flow at the corner combine and generate instantaneous strong wind. This strong corner wind will become stronger with increasing building height. (Chien, Chun, Ming, & Chi, 2015)

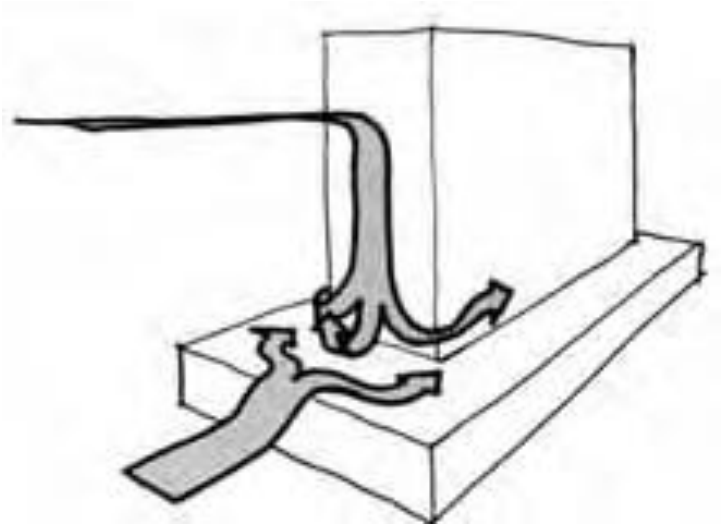


Figure 2.26 Tower and podium effect

(Source: Bennet, Kepka, Wang, & Watt, 2007)

2.10 Building Response Due to Wind Effects

Wind produces three different types of effects on structure: static, dynamic and

Aerodynamic. The response of load depends on type of structure. When the Structure deflects in response to wind load then the dynamic and aerodynamic effects should be analyzed in addition to static effect. (Sukanta , n.d.)

There are several different phenomena giving rise to dynamic response of structures in wind. These include buffeting, vortex shedding, galloping and flutter. Slender structures are likely to be sensitive to dynamic response in line with the wind direction as a consequence of turbulence buffeting as shown in figure 2.27. Transverse or cross-wind response is more likely to arise from vortex shedding or galloping but may also result from excitation by turbulence buffeting. (Mendis, Ngo, Haritos, Samali, & Cheung, 2007)

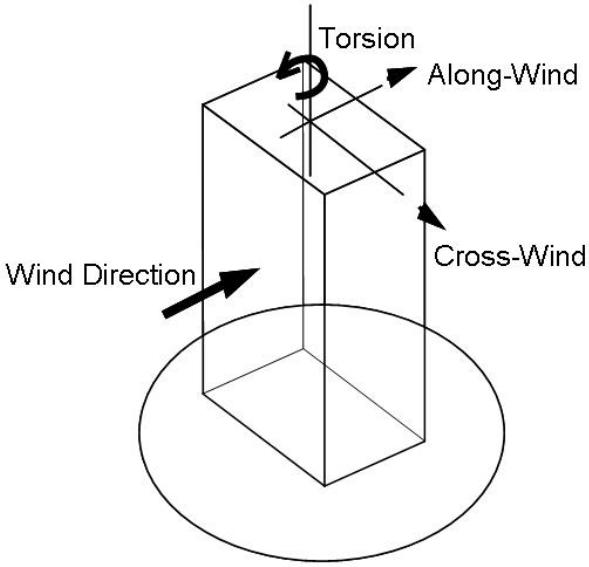


Figure 2.27 Wind Response Directions

(Source: Mendis, Ngo, Haritos, Samali, & Cheung, 2007)

2.10.1 Wind induced oscillation

There are three forms of wind induced motion as follows: galloping, flutter and ovalling.

2.10.1.1 Galloping

Galloping is transverse oscillations of some structures due to the development of aerodynamic forces which are in phase with the motion. It is characterized by the progressively increasing amplitude of transverse vibration with increase of wind speed. Non circular cross section are more susceptible to this type of oscillation (Sukanta , n.d.)

2.10.1.2 Flutter

According to (Sukanta , n.d.), flutter is unstable oscillatory motion of a structure due to coupling between aerodynamic force and elastic deformation of the structure. Perhaps the' most common form is oscillatory motion due to combined bending and torsion. Long span suspension bridge decks or any member of a structure with large values of d/t (where

d is the depth of a structure or structural member. parallel to wind stream and t is the least lateral dimension of a member) are prone to low speed flutter.

2.10.1.3 Ovalling

Enclosed structures with open ends at one or both ends such as oil storage tanks, and natural draught cooling towers in which the ratio of the diameter of minimum lateral dimension to the wall thickness is of the order of 100 or more, are prone to ovalling oscillations. These oscillations are characterized by periodic radial deformation of the hollow structure. (Sukanta , n.d.)

2.10.2 Dynamic component which causes the oscillation of structures

The dynamic components that causes the oscillation of structures are: wind gust, vortex shading and buffeting which will be explained below.

2.10.2.1 Wind gust

Wind gust is a sudden brief increase in the speed of the wind followed by a lull. According to National Weather Service observing practice, gusts are reported when the peak wind speed reaches at least 30 km/h and the variation in wind speed between the peaks and lulls is at least about 16 km/h. Gusts at the ground are caused by either turbulence due to friction, wind shear or by solar heating of the ground. These three mechanisms can force the wind to quickly change speed as well as direction.

i. In the case of friction, gusts are generated when wind blows around buildings, trees or other obstacles. This type of gustiness is generally largest near tall buildings and alley ways and least over large water bodies.
ii. A wind shear is a change in the wind over a distance. This can be a change in wind direction, wind speed or both.

iii. On sunny days wind gusts can be generated by rising air currents when the ground is heated. This can generate a thermal of warm air that rises, with air from above sinking to replace the rising thermal. This descending air can cause wind gusts.

According to (Sukanta , n.d.), the wind velocity at any location vary considerably with time. In addition to a steady wind there are effects of gusts which last for few seconds. And yields a more realistic assessment of wind load. In practice the peak gust are likely to be observed over an average time of 3.5 to 15 secs depending on location and size of structure. The intensity of gusts is also related to the duration of gusts that affects structures. Larger structure will be affected more by gust of larger duration and thus subjected to smaller pressure compared to smaller structure. The gust effect factor accounts for additional dynamic amplification of loading in the along-wind direction due to wind turbulence and structure interaction. It does not include allowances for across-wind loading effects, vortex shedding, instability due to galloping or flutter, or dynamic torsional effects. Buildings susceptible to these effects should be designed using wind tunnel results.

This factor accounts for the increase in the mean wind loads due to the following factors:

i. Random wind gusts acting for short durations over entire or part of structure.
ii. Fluctuating pressures induced in the wake of a structure, including vortex shedding forces.
iii. Fluctuating forces induced by the motion of a structure.

2.10.2.2 Vortex shading

Vortex shedding occurs when wind flows past a bluff (un-streamlined) body, such as a building, which causes the flow to separate from the surface of the structure rather than follow the body contour (see figure 2.28 below). The shed vortices produce a force that

acts on the body in the crosswind direction. At relatively low wind speeds the spiral vortices are created periodically and symmetrically from both sides of the body. Since these vortices are symmetrical, the loads tend to cancel each other out and the effect of vortex shedding can be ignored. However, at higher wind speeds, the vortices are shed alternatively, i.e. on one side first then the other. As a result, alternating low pressure zones are formed on the downstream side of the building and a fluctuating transverse load is created. This causes the building to move towards the low pressure zone. If the natural frequency of the structure coincides with the frequency of the vortex shedding, then large amplitude displacement response may occur. This is often called the critical velocity effect. (Engineers and technical designers, n.d.)

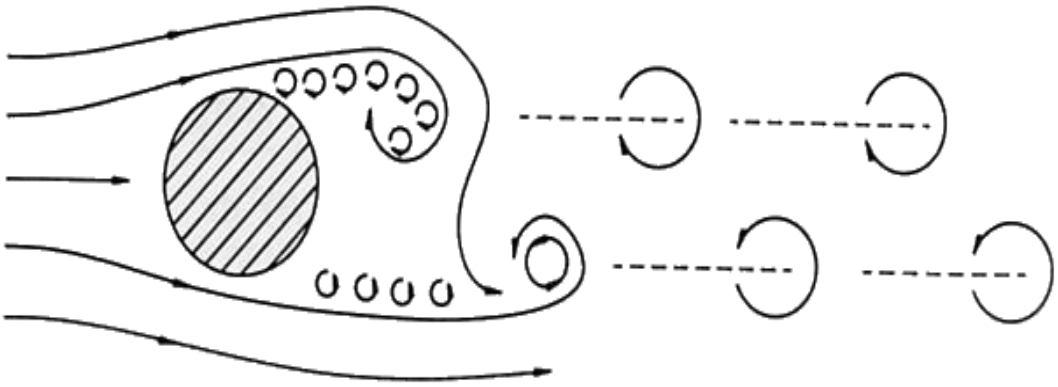


Figure 2.28 vortex formation

(Source: Mendis, Ngo, Haritos, Samali, & Cheung, 2007)

When wind acts on a bluff body, forces and moments in three mutually perpendicular directions are generated out of which three are translational and three rotational. For civil and structures the force and moment corresponding to the vertical axis (lift and yawing moment) are of little significance as shown in figure 2.29. Therefore the flow of wind is considered two dimensional consisting of along wind response and transverse wind response. (Sukanta , n.d.)

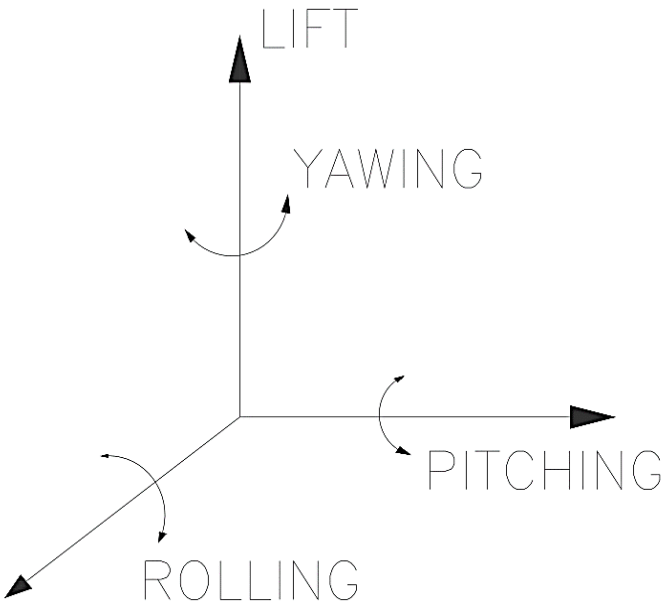


Figure 2.29 Vortex shading

(Source: Sukanta , n.d.)

When the wind blows across a slender structural member, vortices are shed alternately from one side and then the other, giving rise to a fluctuating force acting at right angles to the wind direction. This organized pattern of vortices is referred to as von Karman Vortex Street see figure 2.30. A structural member may be considered slender in this context if the aspect ratio exceeds 20. (Giosan & Eng, n.d.)

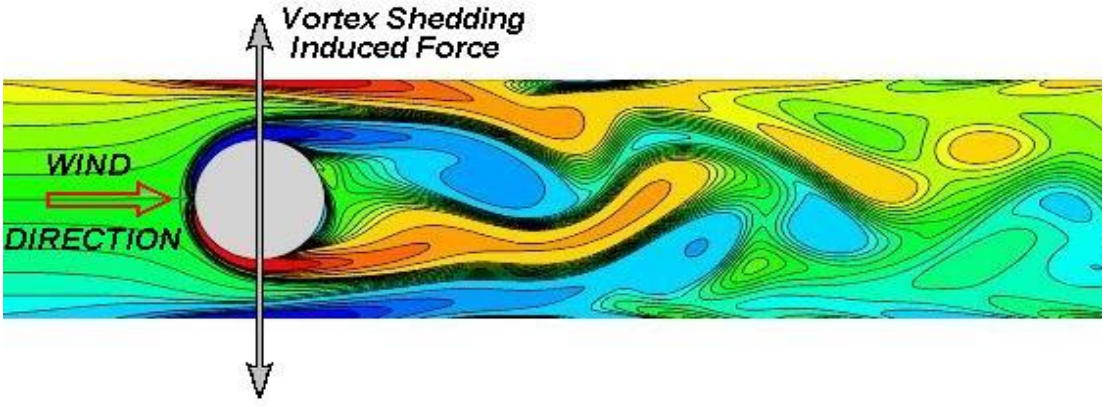


Figure 2.30 Vortex Shedding phenomenon induced by wind flowing over a cylinder

Source: (Giosan & Eng, n.d.)

For lightly damped members, which are free to oscillate, large amplitude vibrations in the plane normal to the wind may develop when the vortex shedding is in resonance with one of the natural frequencies of vibration. Although this is most likely to occur for the lower modes of vibration, vortex shedding induced effects for very flexible members may also be important for higher modes. The character of the vortex shedding forces for circular cylinders depends on the Reynolds number. (Giosan & Eng, n.d.)

Re = VD/v

Where:

V= wind speed [m/s]

D= structure diameter [m]

v = kinematic viscosity [m/s].

Vortex shedding tends to be irregular unless the structural motion is sufficiently large to organize the fluctuating flow around the body. This phenomenon, referred to as “locking in”. When the lock-in phenomenon occurs, in some cases, severe vibration has persisted long enough to cause fatigue cracking or structural failure (Giosan & Eng, n.d.) see figure 2.31 below.



Figure 2.31 Antenna Tower Fatigue Failure under lock in

(Source: Giosan & Eng, n.d.)

2.10.2.3 Buffeting

Buffeting is a high-frequency forced vibration that is caused by airflow separation from one object striking another as a result of a sudden impulse of increased load. (Engineers and technical designers, n.d.)

2.11 Wind Loading on Tall Buildings

Wind loading can be defined as the force on a structure arising from the impact of wind on it. Wind load is classified into horizontal wind load for structural frames, roof wind load for structural frames and wind load for components/cladding as shown in figure 2.32. The wind load for structural frames is calculated from the product of velocity pressure, gust effect factor and projected area. The wind load for components/cladding is calculated from the product of velocity pressure, peak wind force coefficient and subject area. (Uematsu, Sone, & Noguchi, 2003).

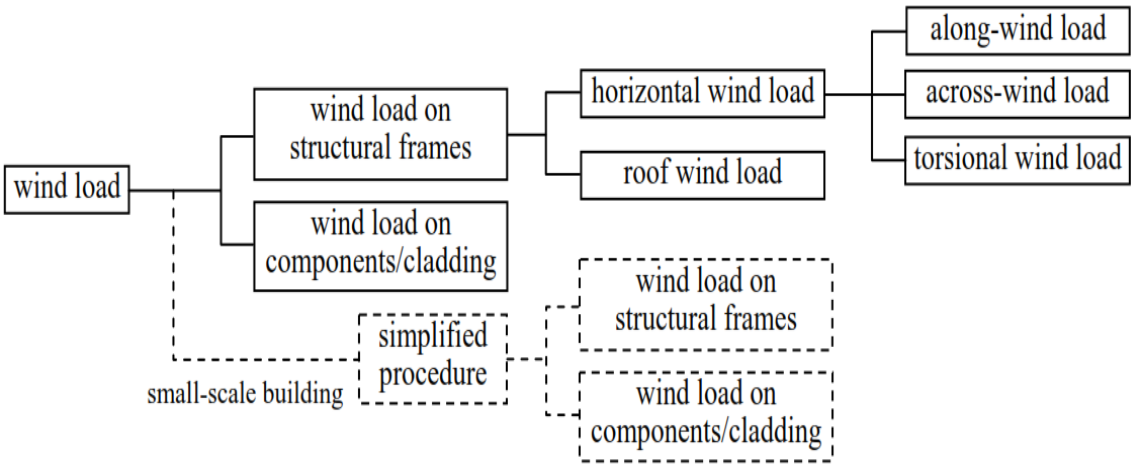


Figure 2.32 Classification of wind loads

(Source: "Recommendations for Loads on Buildings", 2006)

2.11.1 Along wind loading

The along-wind loading or response of a building due to buffeting by wind can be assumed to consist of a mean component due to the action of the mean wind speed (e.g., the mean-hourly wind speed) and a fluctuating component due to wind speed variations

from the mean (Mendis, Ngo, Haritos, Samali, & Cheung, 2007). The fluctuating wind is a random mixture of gusts or eddies of various sizes with the larger eddies occurring less often (i.e. with a lower average frequency) than for the smaller eddies. The natural frequency of vibration of most structures is sufficiently higher than the component of the fluctuating load effect imposed by the larger eddies, i.e. the average frequency with which large gusts occur is usually much less than any of the structure's natural frequencies of vibration and so they do not force the structure to respond dynamically. The loading due to those larger gusts (which are sometimes referred to as "background turbulence") can therefore be treated in a similar way as that due to the mean wind. The smaller eddies, however, because they occur more often, may induce the structure to vibrate at or near one (or more) of the structure's natural frequencies of vibration. This in turn induces a magnified dynamic load effect in the structure which can be significant.

2.11.2 Across-wind and torsional wind loading

Both across-wind vibration and torsional vibration are caused mainly by vortices generated in the building’s wake. These vibrations are not so great for low-rise buildings. However, with an increase in the aspect ratio caused by the presence of high-rise buildings, a vortex with a strong period uniformly generated in the vertical direction, and across-wind and torsional wind forces increase (Uematsu, Sone, & Noguchi, 2003).

In general, responses to across-wind vibration and torsional vibration depending on wind speed increase more rapidly than responses to along-wind vibration. Under normal

conditions, along-wind responses to low wind speed are larger than across-wind responses. However, across-wind responses to high wind speed are larger than along-wind responses see figure 2.33. The wind speed at which the degrees of along-wind response and across-wind response change places with each other differs depending on the height, shape and vibration characteristics of the building

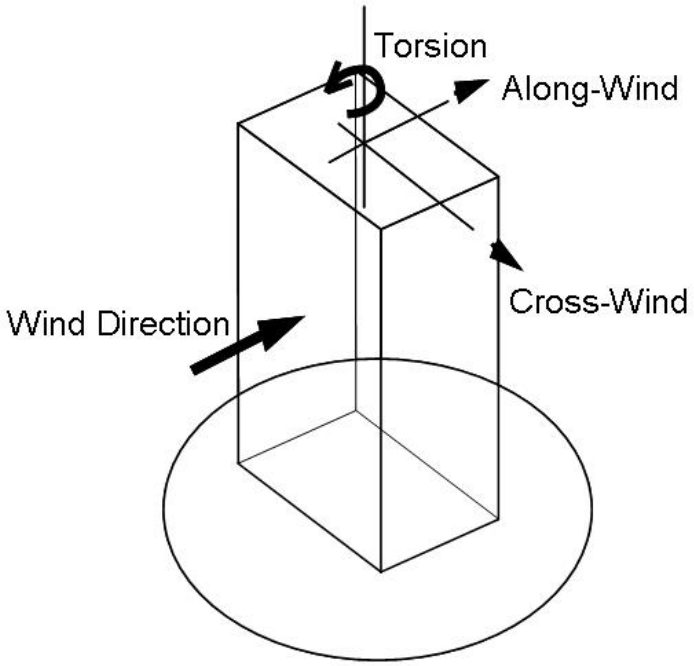


Figure 2.33 Wind response

(Source: Mendis, Ngo, Haritos, Samali, & Cheung, 2007)

2.12 Types of Wind Load Forces on Buildings

Shear Load – Wind pressure that is horizontal and could make a building tilt.

Lateral Load – A pulling and pushing horizontal pressure that can cause a building to move off its foundation.

Uplift Load – Pressures from wind flow that cause lifting effects.

3.0 METHODOLOGY

3.1 Introduction

The aim of this research is to draw a distinction or hierarchy in basic high rise building forms in order of effects they receive from high wind speed and how this wind effects can be minimized through design. However, wind speed is one of the main factors affecting the design of high rise buildings. Thus, assessing the history of wind speed at the proposed site is important in determining the types of threat to be dealing with, especially in urban areas where different variables affect wind flow. These variables include urban settings, surface cover and vegetation (Yuen, Zanchetta, & Battle, 2004). Urban wind flow and wind flow around buildings are carried out using a variety of available tools including: In-situ measurements, wind tunnel tests, and computer simulations.

3.2 Source of Data

This research is focusing on Eko Atlantic city Lagos as shown in figure 3.1. The location was chosen because of its high tendency to wind attacks. Thus judging from local history in Lagos it was stated that maximum sustain wind speeds reach up to 111-120km/h which is equivalent to violent wind storm and very close to hurricane scale (Ochereome, 2012). However, with the site been located on a reclaimed land in Atlantic Ocean, it is expected that the wind speed will increase to a magnitude equivalent to a hurricane scale.

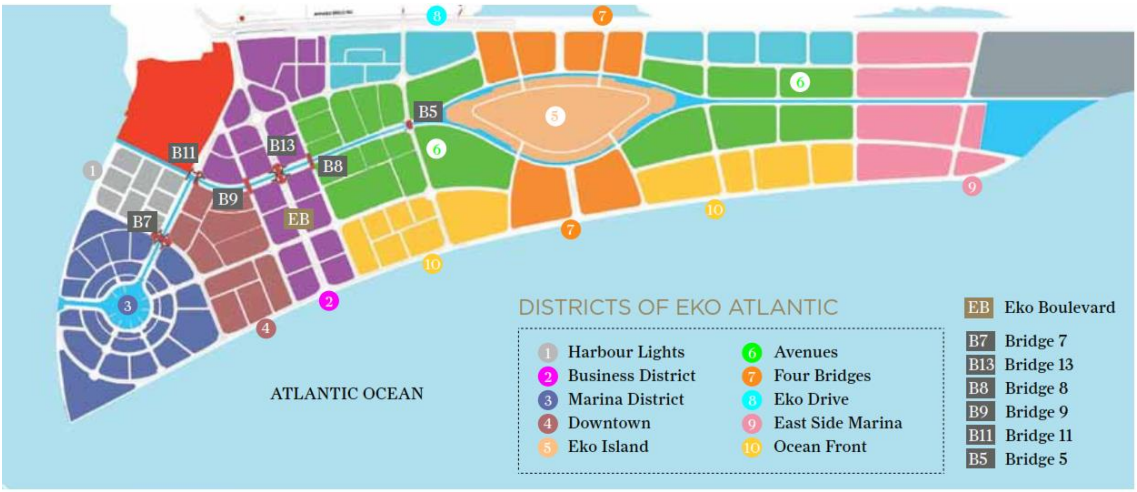


Figure 3.1 Eko Atlantic City Lagos

(Source: south energyx nigeria limited, 2013)

3.3 Research Design

This research adopts an experimental and exploratory approach to frame the answers to its research aim and objectives.

3.3.1 Experimental approach

According to (Jha, 2010), the most common research tools used to understand wind flow within the built environment are:

i. In situ measurements.

ii. Wind tunnel test.

iii. Computational fluid dynamics simulations (CFD).

However, all of these tools have specific advantages and disadvantages that define the suitability of the tool for a certain analysis. From the works of (Islam, 2012) he analyzed and compared all these tools in order of their importance see table 3.1 below.

Table 3.1: Comparison between in-situ measurements, wind tunnel tests and computer simulations (CFD)

	Tools arranged in descending order
High Accuracy	In Situ Measurements – wind tunnel - CFD
High Visualization	CFD – Wind tunnel – in Situ Measurements
Assessing wing flow in existing urban areas	In Situ Measurements – CFD – Wind Tunnel
Assessing wind flow for future planned urban areas	CFD – Wind tunnel – In Situ Measurements
Lowest cost	CFD – Wind tunnel – In Situ Measurements
Less time consumed	CFD – Wind tunnel – In Situ Measurements
Availability to architects	CFD – Wind tunnel – In Situ Measurements

(Source: Islam, 2012)

It can be seen from the table that of all the tools used for assessing wind flow in the built environment, architects favor CFD simulation over other available tools because of its potentials in comparing design alternatives, its high visualization representation and its ease of use when compared with other wind assessment tools. However, the type of CFD to be used in this research is Autodesk Flow Design, because of its lightness, speed, availability, compatibility and Accuracy. A great number of commercial CFD programs are available commercially. Out of these Autodesk CFD was selected because it provides a free license for academic use. Other CFDs like Ansys Fluent are used in many scientific papers, but issues with the licensing of its student product prevented this research from using it. Flow Design acts as a wind tunnel simulator, it has an intuitive user interface and interoperability with Revit and Inventor so you can understand and analyze airflow patterns through and around structures in built-up areas. Identify hazards caused by

moving air, such as gusts and downdrafts, and still regions that can contain high concentrations of pollutants.

3.3.1.1 Data collection in Autodesk flow design

Flow Design offers a choice between 2D (horizontal plane) and 3D simulation. 2D is faster, but less accurate than 3D, 2D simulations are mostly used during simple conceptual analysis. Therefore, both were used were necessary.

3.3.1.2 Computational domain dimensions

The computational domain represents the geometry of the region of interest and it cuts off the surroundings, thus the boundary condition of the domain approximates the conditions of the surroundings. The figure 3.2 show the positioning of these boundaries plays an important role in the accuracy of the simulation and the size of the computational domain in the vertical, lateral and flow directions depends on the area that shall be represented.

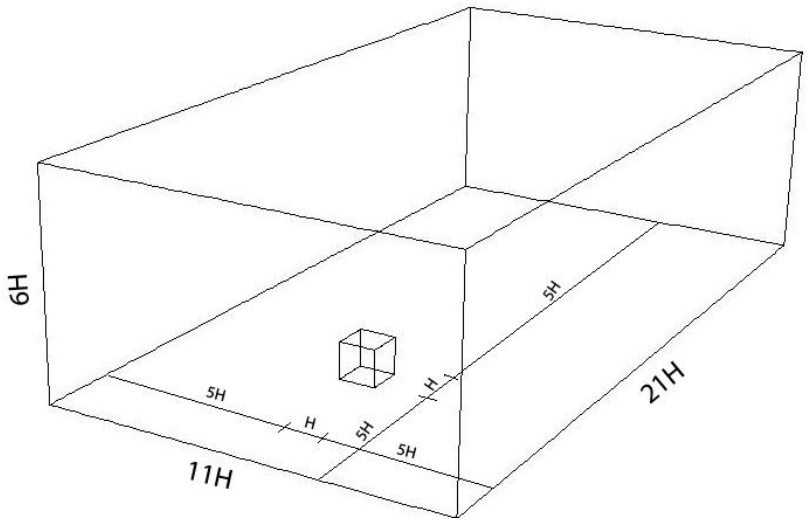


Figure 3.2: Computational domain dimensions for a flow around a surface mounted cube of height

(Source: Islam, 2012)

3.3.1.3 Computational domain boundary conditions

As cited in (Islam, 2012), the domain represents a truncation of part of the surrounding of the flow problem, thus this truncation leads to artificial boundaries, where these boundaries have to prescribe values of certain physical quantities. Assigning these physical quantities to the boundaries should be treated with care as an improper implementation can result in inaccurate simulation of the real flow problem, as well as its effect on the stability and convergence speed of the solution.

3.3.1.4 Computational mesh

The computational domain was set up as shown in Figure 3-3 according to the recommendations by (Blocken, 2015) Meshing was performed using the programs built-in automated meshing function with the default settings. The fineness was set to result in a mesh with 1.2 million tetrahedral elements. For boundary conditions, the inflow was set as a normal velocity with the speed set to the ambient wind speed. The outflow condition was set as a gage pressure of 0 (free outflow), and the top and side boundary conditions were set to slip/symmetry. The k-ε turbulence model was used

3.3.2 Exploratory approach

This research also employs the use of survey to collect data in order to justify its research aims and objectives. Architectural surveys typically document buildings through drawing and sketching along with other demographic characteristics.

3.3.2.1 Methods of data collection

i. Personal observation
ii. Photographs/sketches
iii. Physical scaled drawings

The physical scaled drawing obtained from the above instruments of data collection will be simulated under high wind to study airflow around it and how it respond to the wind effects.

4.0 DATA PRESENTATION AND RESULTS

4.1 Case Study

In this chapter, the results of the case study conducted and the analysis carried out is presented. These variables of study were developed from an extensive review of the literature and similar studies. The case study focuses on; building form, orientation, and building height. Plate 4.1 shows a pictorial view of Necom house.

4.2 Case Study 1: Necom Tower



Plate 4.1 Necom house

(Source: author's field work)

4.2.1 Background information

NECOM House (formerly NITEL Tower) 160 m (520 ft) tall; is a highrise building in Lagos, Nigeria see plate 4.1 above. The 32-story building was completed in 1979, and house the headquarters of NITEL. The communications spire at the top of the tower serves as a lighthouse beacon for Lagos Harbor. The building is constructed of concrete. The building is the tallest in Nigeria.

4.2.2 Building form

The building is rectangular in plan with few architectural details as shown in figure 4.1 below. The approach width is 18m, while the width from the back is 15m whereas the building length is 41m and the height is 160m including the mast at the roof top.

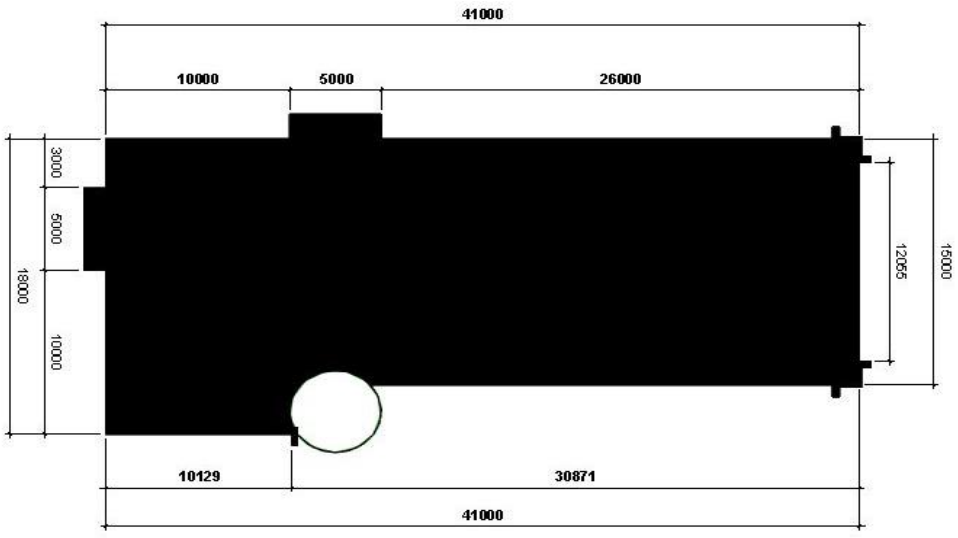


Figure 4.1 Outline plan dimension of Necom house, Lagos.

(Source: author's sketch)

4.2.3 Building orientation

The building is oriented along North West (NW) and South East (SE) direction as shown in plate 4.2 below. On a coordinate of $6^{0}26^{1}45.93^{11}$N and $3^{0}23^{1}50.51^{11}$E.



Plate 4.2 satellite view of Necom house

(Source: google earth pro 7)

4.2.4 Important notes

This research focuses on only the effects of wind on different individual building forms. Therefore, the simulations below for the case studies did not capture the surrounding or neighboring buildings.

Note that, any changes made to the; orientation, building forms, height, width, wind speed, domain, architectural details or any technical adjustment may change the simulation results in this research.

4.2.5 Case study simulation analysis

A virtual model of the building was prepared using Revit, and then simulated using Autodesk flow design. The building was assessed base on: pedestrian wind, wind loading and vortex shedding formation. Figure 4.2 shows the properties, location and nature of flow pattern around and object.

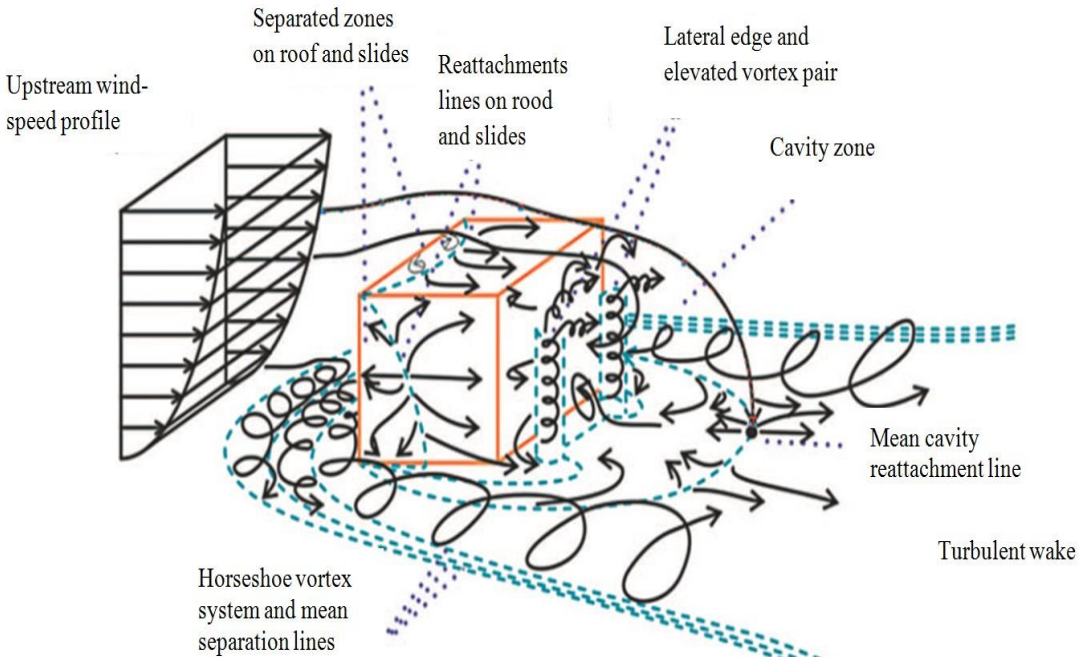


Figure 4.2 Regions of high surface wind speeds around a tall building

(Source: Mohamed & John, june 2013)

4.2.6 Pedestrian wind speed

To assess the pedestrian wind speed the average and the highest wind speed were used in order to obtain accurate values. 5m/s and 31m/s respectively for south west trade wind see figure 4.3 below.

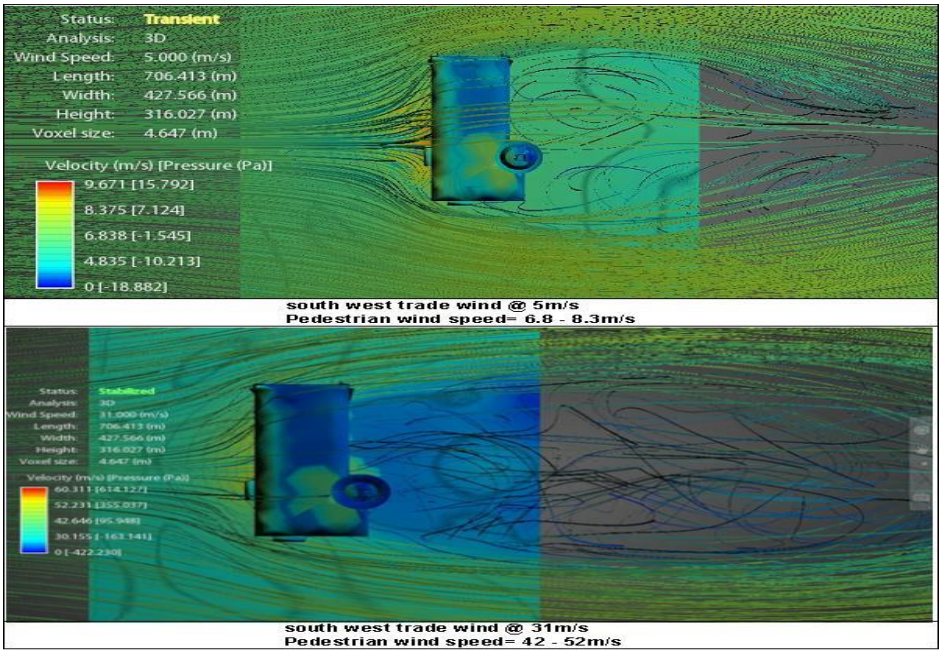


Figure 4.3 Pedestrian wind speed @ 1.5m above the ground

(Source: Authors simulation 2016)

4.2.6.1 Discussion of result

The following table from (Mohamed & John, 2013) lists a range of comfort classes based on wind speeds and limiting criteria. These classes attempt to quantify pedestrian comfort assuming suitable attire. They only consider wind speed and do not account for other weather conditions such as temperature and humidity as shown in table 4.1 below.

Table 4.1 Classes of comfort under different wind speed

COMFORT CLASS	WIND CONDITION	ACTIVITY DESCRIPTION
Sitting	Wind speed < 3.9 m/s Occurs > 70 % of the time	Acceptable for sedentary activities.
standing	Wind speed < 6.1 m/s Occurs > 80 % of the time	Acceptable for standing, strolling, and other slow movements.
walking	Wind speed ≤ 8.3 m/s Occurs > 80 % of the time	Acceptable for walking, running, and other rigorous activities
uncomfortable	Wind speed > 8.3 m/s Occurs > 20 % of the time	Unacceptable for walking.
Dangerous	Wind speed > 25 m/s Occurs > 0.01 % of the time	Dangerous for walking

(Source: Mohamed & John, june 2013)

Therefore, from the Table 4.1 it was noticed that the pedestrian wind speed at 5m/s is between the range of 6.8 – 8.3 m/s which is acceptable for walking, running, and other rigorous activities. Whereas the pedestrian wind speed at 31m/s is between the range of 42 – 52 m/s which is dangerous for walking. However, this effect can be reduced by urban obstacles like other buildings around or by planting large trees at the wind ward side as explained by davenports classification of aerodynamic roughness.

4.2.7 Wind loading

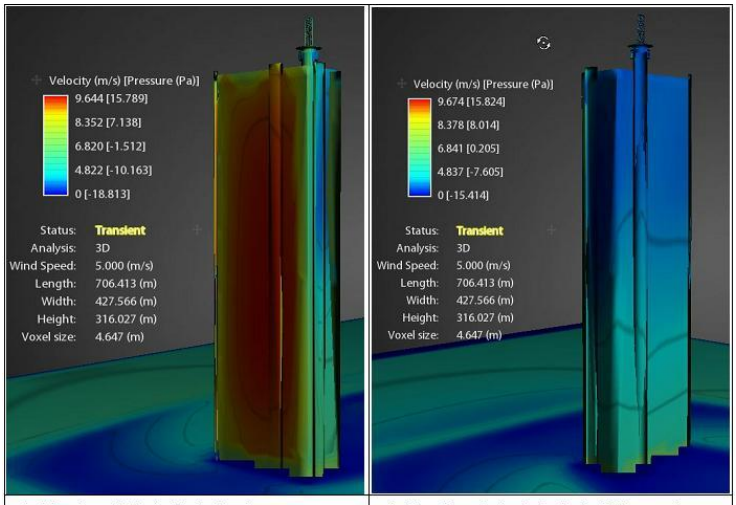
To assess the wind loading on the structure, different variables were analyzed at 5m/s and 31m/s.

i. Incident wind velocity: gives idea of incident wind speed at the balconies and windows at the impingement point.

ii. Incident pressure: positive incident pressure gives idea of pressure exerted at the impingement point or wind ward side. Whereas negative pressure shows the amount of suction generated at the wake of the building (lee ward side).

iii. Drag force: The drag force is the amount of force imparted on the building by the wind as it flows into, over, and around it. Higher values of force indicate a greater resistance to the flow while Lower values indicate less wind resistance

iv. Drag coefficient: The drag coefficient is a dimensionless quantity that represents the amount of aerodynamic drag of the object. Higher values indicate a greater resistance to the flow, lower values indicate less wind resistance see figure 4.4 and 4.5.



wind loading @ 5m/s @ the impingement	wind loading @ 5m/s @ the buildings wake
- incident velocity = 9.644m/s	- velocity = 0 - 5m/s
- incident pressure = 15.789 pa	- pressure = - 15.414 pa

Figure 4.4 Wind loading

(Source: Authors simulation, 2016)

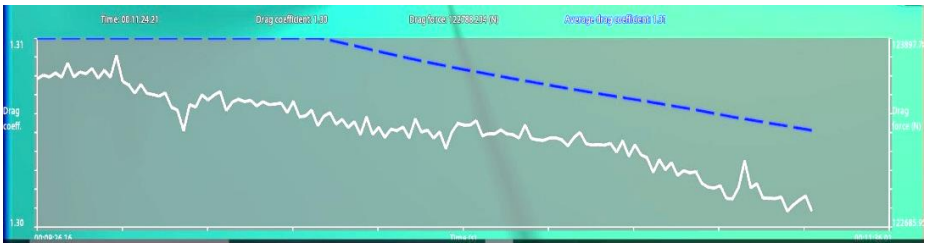


Figure 4.5 Drag force = 122788.234 N drag cooefficient = 1.30

(Source: Authors simulation, 2016)

4.2.7.1 Discussion of result

i. From the result obtained above it was observed that the incident wind velocity was 9.644m/s which is considered uncomfortable for walking as opined by (Mohamed & John, 2013) and as shown in his Table 4.1. Therefore, this means that staying at the balconies is not advised. However, the wind velocity at the wake of the building was recorded to be within the range of 0 – 5 m/s which is acceptable for staying at the balconies.

ii. The incident pressure at the impingement and the wake of the building was 15.789 and -15.414 pa respectively. Negative pressure zones indicate suction and this is responsible for pulling out of glass panels, hence the relationship between the incident velocity (9.6m/s) and the pressure (positive and negative) exerted on the building doesn't have the enough magnitude to cause destruction as discussed in the Beaufort scale.

iii. The relationship between the; incident velocity, pressure, drag force, and drag coefficient can be used to test for wind pressure resistance of a glass as shown in table 4.2 below.

Table 4.2 Allowable load of glasses

Types	**Thickness (mm)**	**Average Maximum Failure load W(kg)**	**Allowable Load Wa (kg)**
Float Glass	2	225	90
	3	450	180
	4	650	260
	5	900	360
	6	1100	440
	8	2000	800
	10	2500	1000
	12	3000	1200
	15	4250	1700
	19	6550	2600
Tempered Glass	4	1950	780
	5	2700	1080
	6	3300	1320
	8	6000	2400
	10	7500	3000
	12	9000	3600
	15	12750	5100
Annealed	3+3	625	250
Laminated	5+5	1350	540
	6+6	1800	720
	8+8	2875	1150
	10+10	4200	1680
	12+12	5770	2300
	15+15	8550	3420
	19+19	13100	5245

(Source: Kien Safety Glass Sdn Bhd)

From Table 4.2, Scale 3 types of glasses were selected, one from each type of glass. The selected glasses will be used to benchmark the wind loading exerted on the cladding.

The wind pressure can be approximated by:

Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

The density of air is about 1.25 kg/m3.

Drag coefficient depends on the shape of the body. It has order of magnitude 1 and is dimension less. The wind speed must be expressed in m/s. In that case the pressure has unit's kg/m/s2, i.e. N/m2. See table 4.3

Parameters: incident wind speed = 9.644m/s, Drag coefficient = 1.3

Pressure = ½ x (1.25) x $(9.644)^2$ x (1.3)

½ x 1.25 x 93 x 1.3 = 75.5625pa

75.5625pa = 75.5625 N/m^2 = 755.625 N

755.625 N = 77.052 kg.

Table 4.3 Suitability of Glasses

wind pressure		**77.052kg**	**77.052kg**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.3 above it is observed that the wind pressure exerted on the glasses for both type of glasses is not enough to cause destruction.

4.2.8 Wind loading at 31m/s

Simulation results for wind loading at 31m/s as shown if figure 4.6 and 4.7

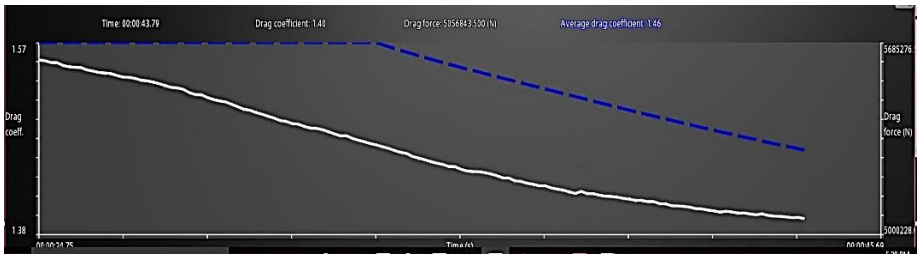


Figure 4.6 Relationship between drag force and drag coefficient

(Source: Authors simulation, 2016)

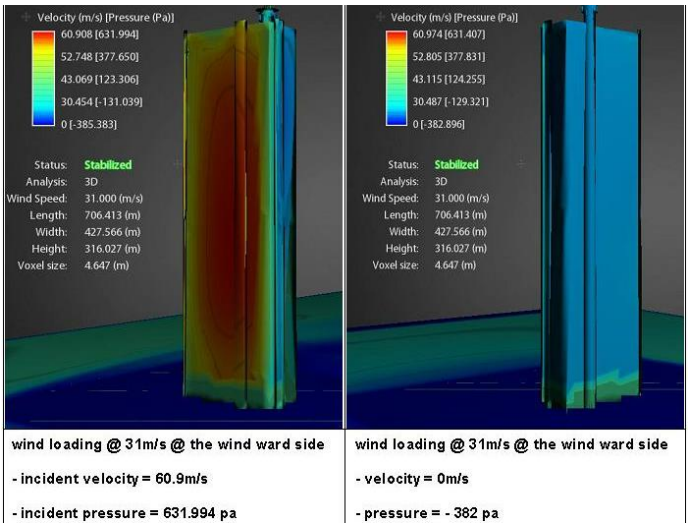


Figure 4.7 Wind loading

(Source: Authors simulation, 2016)

Simulation results: incident velocity = 60.9m/s

Incident pressure = 631.994pa

Drag force = 5056843.500N

Drag coefficient = 1.4

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (60.9)2 x (1.4)

½ x 1.25 x 3708.81 x 1.4 = 3245.2 pa

3245.2 pa = 3245.2 N/m^2 = 32452.1 N

32452.1 N = 3309.1 kg. See table 4.4

Table 4.4 Suitability of glasses

wind pressure		**3309.1 kg.**	**3309.1 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

4.2.8.1 Discussion of result

From Table 4.4 it is observed that the wind pressure exerted on the glass for both type of glasses exceeded the average maximum failure load (kg). Therefore, it is expected that the type of glazing to be used should be of greater value than the ones selected in the table.

4.3 Case Study 2: Union Bank

4.3.1 Background information

Union Bank Building is a skyscraper in Lagos with a total height of 124 m (407 ft.) as shown in plate 4.3 below. The 28-story building serves as the headquarters of the Union Bank of Nigeria. The building is constructed from concrete with some of its façade been glazed.



Plate 4.3 Union Bank towers

(Source: Authors field work, 2016)

4.3.2 Building form

The building is rectangular in plan with few extrusions on the south west and on the western facade. The approach width is 30m, whereas the building length is 50m and the height is 124m as shown in figure 4.8.

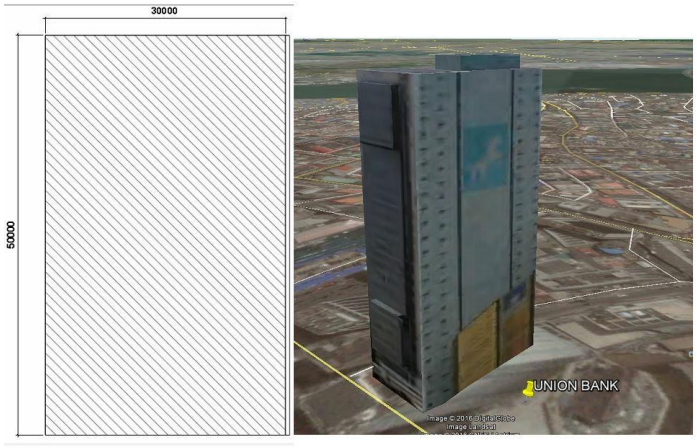


Figure 4.8 Union Bank building

(Source: Authors sketch / Google Earth pro 2016)

4.3.3 Building orientation

The longer part of the building is oriented along North East (NE) and South West (SW) direction as shown in figure 4.9 below. On a coordinate of $6^{0}27^{1}08.32^{11}$N and $3^{0}23^{1}16.52^{11}$E.



Figure 4.9 Satellite view

(Source: Authors streaming, 2016)

4.3.4 Case study simulation analysis

A virtual model of the building was prepared using Revit, and then simulated using Autodesk flow design. The building was assessed base on: pedestrian wind, wind loading and vortex shedding formation. Figure 4.10 shows the simulation result for pedestrian wind

4.3.5 Pedestrian wind speed at 5m/s

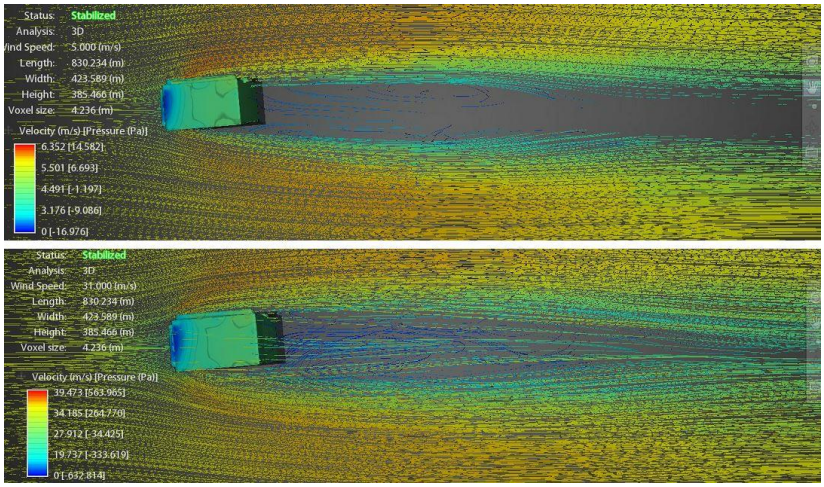


Figure 4.10 Pedestrian wind speed

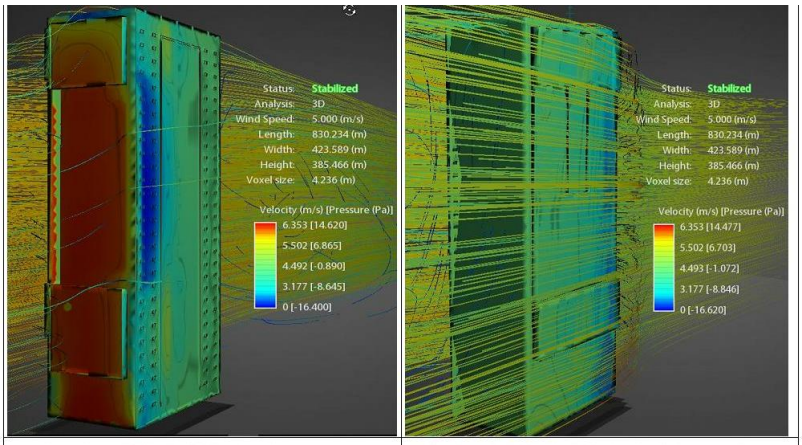
(Source: Authors simulation 2016)

4.3.5.1 Discussion of result

From the result obtained above in figure 4.10, the pedestrian wind speed is recorded to be 6.352m/s. However according to (Mohamed & John, 2013), speed at 6.352 falls within the class of wind that is acceptable for walking, running, and other rigorous activities. Whereas the pedestrian wind speed at 31m/s is recorded to be 39.5m/s however wind speed of this kind falls under dangerous class of wind which is dangerous for walking and other activities.

4.3.6 Wind loading at 5m/s

The simulation results obtained for wind loading at 5m/s. See figure 4.11 and 4.12



wind loading @ 5m/s @ the impingement	wind loading @ 5m/s @ the buildings wake
- incident velocity = 6.4 m/s	- velocity = 3 - 4 m/s
- incident pressure =14.6 pa	- pressure = - 8.8 pa

Figure 4.11 Wind loading

(Source: Authors simulation, 2016)



Figure 4.12 Drag coefficient

(Source: Authors simulation, 2016)

4.3.6.1 Discussion of result

i. From the result obtained in figure 4.11 and 4.12 above is was observed that the incident wind velocity at 5m/s was 6.4m/s with is considered acceptable for walking and other activities as opined by (Mohamed & John, 2013) and as shown in his table previously. However the wind velocity at the wake of the building has a pressure of -8.8 pa, with is too low cause harm.

ii. Simulation results: incident velocity = 6.4 m/s

Incident pressure = 14.6 pa

Drag force = 65456.859 N

Drag coefficient = 0.97

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (6.4)^2 x (0.97)

½ x 1.25 x 40.96 x 0.97 = 24.83 pa

24.83 pa = 24.83 N/m^2 = 248.3 N

248.3 N = 25.3 kg. See Table 4.5.

Table 4.5 Suitability of glasses

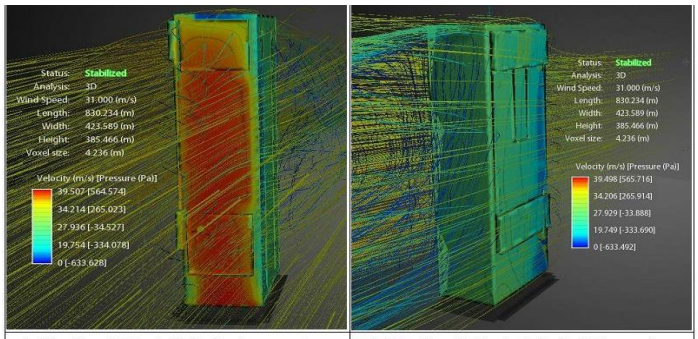
wind pressure		**25.3 kg**	**25.3 kg**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From the above table 4.5 it is observed that the wind pressure (25.3 kg) exerted on the glass for both type of glasses is below the allowable load. And that means that any of the above selected glasses can be suitable.

4.3.7 Wind loading at 31m/s

The simulation results obtained for wind loading at 5m/s. See figure 4.13 and 4.14



wind loading @ 31m/s @ the impingement **- incident velocity = 39 m/s** **- incident pressure =564.6 pa**	**wind loading @ 31m/s @ the buildings wake** **- velocity = 19.7 m/s** **- pressure = - 333.69 pa**

Figure 4.13 Wind loading

(Source: Authors simulation, 2016)

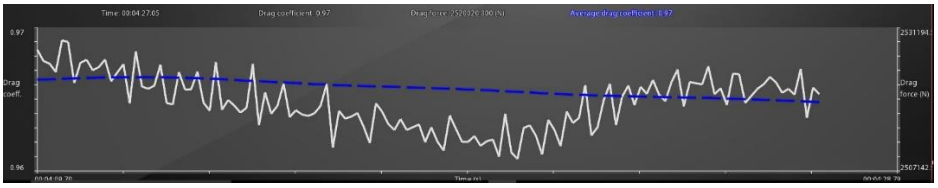


Figure 4.14 Drag coefficient

(Source: Authors simulation, 2016)

4.3.7.1 Discussion of result

i. From the result obtained in figure 4.13 and 4.14 above is was observed that the incident wind velocity at 31m/s was 39 m/s with is considered dangerous for walking and other activities as opined by (Mohamed & John, 2013). The wind velocity at the wake has a pressure of -333.69 pa, with is dangerous to the building

ii. Simulation results: incident velocity = 39 m/s

Incident pressure = 564 pa

Drag force = 2520020 N

Drag coefficient = 0.97

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (39)^2 x (0.97)

½ x 1.25 x 1521 x 0.97 = 922.11 pa

922.11pa = 922.11N/m^2 = 9221.1N

9221.1N = 940.3 kg. See Table 4.6.

Table 4.6 Suitability of glasses

wind pressure		**940.3 kg.**	**940.3 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.6 above it is observed that the wind pressure (940.3 kg.) exerted on the glass for float glass and annealed laminated glass is above the allowable load but did not exceed the maximum failure load, whereas for tempered glass the pressure is below the allowable load. That means tempered glass is more suitable.

4.3.7.2 Important notes

It is important to note that from the simulations above, wind at 5m/s doesn't have enough magnitude to cause serious harm to the building. Therefore, subsequent simulations will be limited to wind speed at 31m/s

4.4 CFD Simulations of Other Building Forms

To validate and fulfill the research aim, other basic building forms were simulated e.g. Aero foil see figure 4.15, square, curvilinear, cylinder, elliptical, parallelogram, polygonal, rectangular, and triangular. Note that, all the building forms simulated below were at 200m high.

4.5 Aero foil Form

Figure 4.16, 4.17 and 4.18 below display the simulation results obtained for pedestrian wind speed, wind loading and drag coefficient respectively.

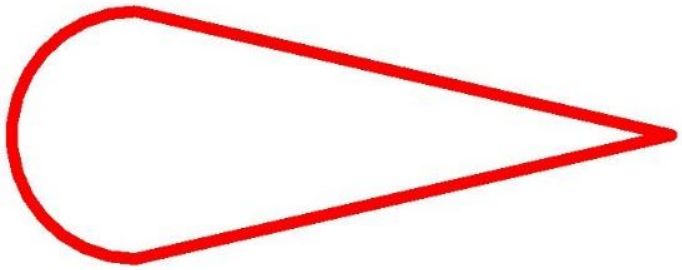


Figure 4.15 Aero foil on plan.

(Source: Authors sketch, 2016)

4.5.1 Pedestrian wind speed

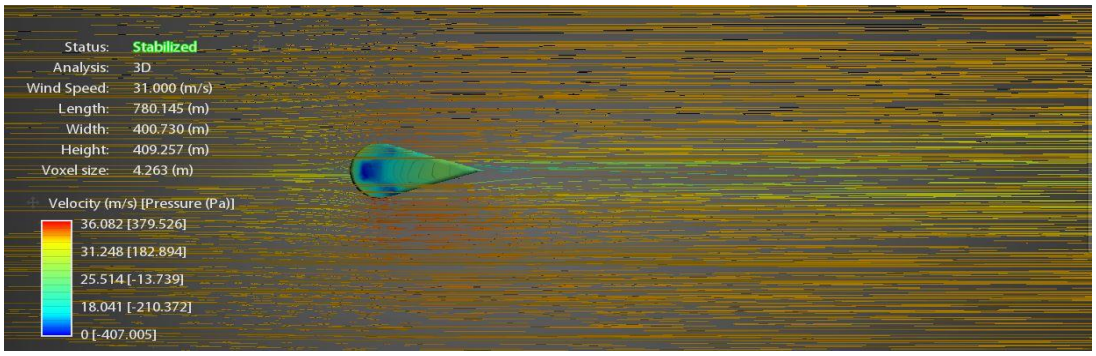


Figure 4.16 Pedestrian wind speed

(Source: Author's simulation result, 2016)

4.5.1.1 Discussion of result

From the above figure 4.16 result it was observed that, the pedestrian wind speed at 31m/s falls between the ranges of 31 – 36 m/s. therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.5.2 Wind loading and ventilation

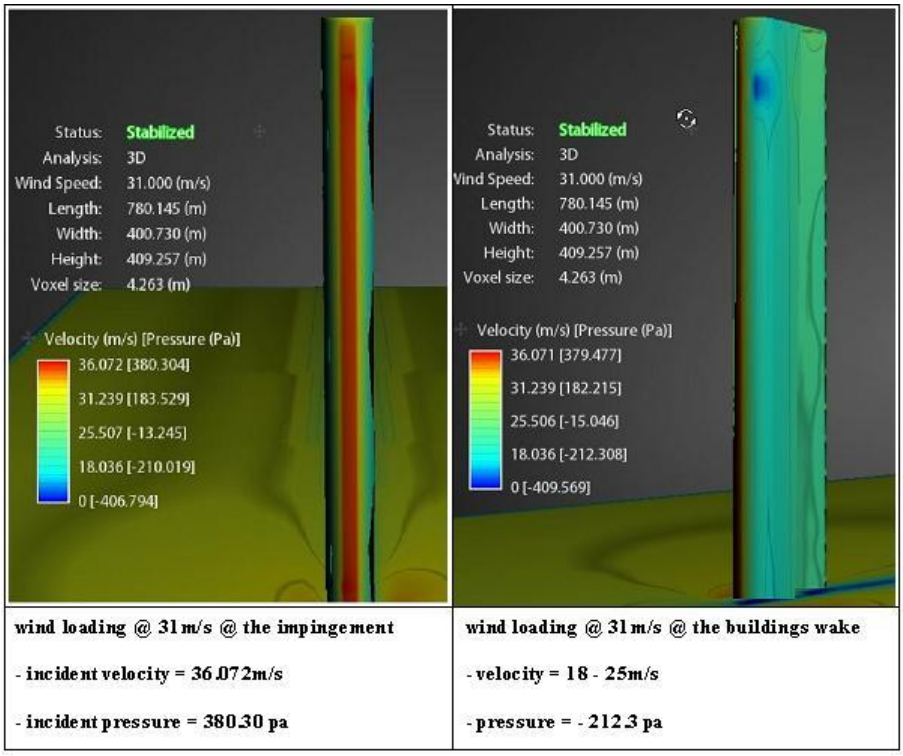


Figure 4.17 Wind loading

(Source: Authors simulation, 2016)

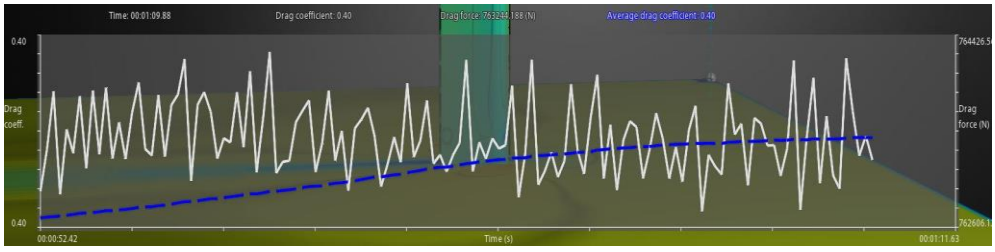


Figure 4.18 Drag coefficient

(Source: Authors simulation result 2016)

4.5.2.1 Discussion of result

i. From the result obtained as shown in figure 4.17 and 4.18 above is was observed that the incident wind velocity was 36.07m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore this means that staying at the balconies is not advised. However the wind velocity at the wake of the building has a pressure of -212.3pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 36.072 m/s

Incident pressure = 380.3 pa

Drag force = 763244.18 N

Drag coefficient = 0.4

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (36.07)^2 x (0.4)

½ x 1.25 x 1301 x 0.4 = 325.2 pa

325.2 pa = 325.2 N/m^2 = 3252 N

3252 N = 331.6 kg. See Table 4.7

Table 4.7 Suitability of glasses

wind pressure		**331.6 kg.**	**331.6 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.7 above it is observed that the wind pressure (331.6 kg) exerted on the glass for both type of glasses is below the allowable load. And that means that any of the above selected glasses can be suitable.

4.6 Square Shaped Form

Figure 4.19 shows the footprint of a square shaped plan whereas figure 4.20, 4.21 and 4.22 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient respectively.

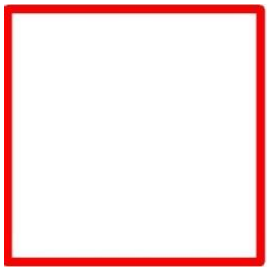


Figure 4.19 Square shaped plan

(Source: Authors sketch 2016)

4.6.1 Pedestrian wind speed

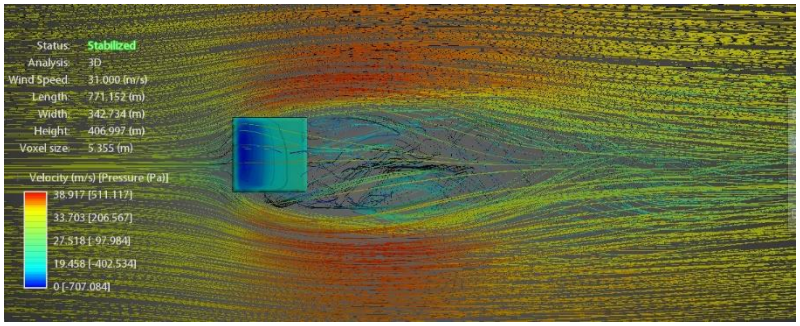


Figure 4.20 Pedestrian wind speed

(Source: Authors simulation, 2016)

4.6.1.1 Discussion of result

From the simulation result above in figure 4.20 it was observed that, the pedestrian wind speed at 31m/s falls between the ranges of 33.7 – 38.9 m/s. therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.6.2 Wind loading and ventilation

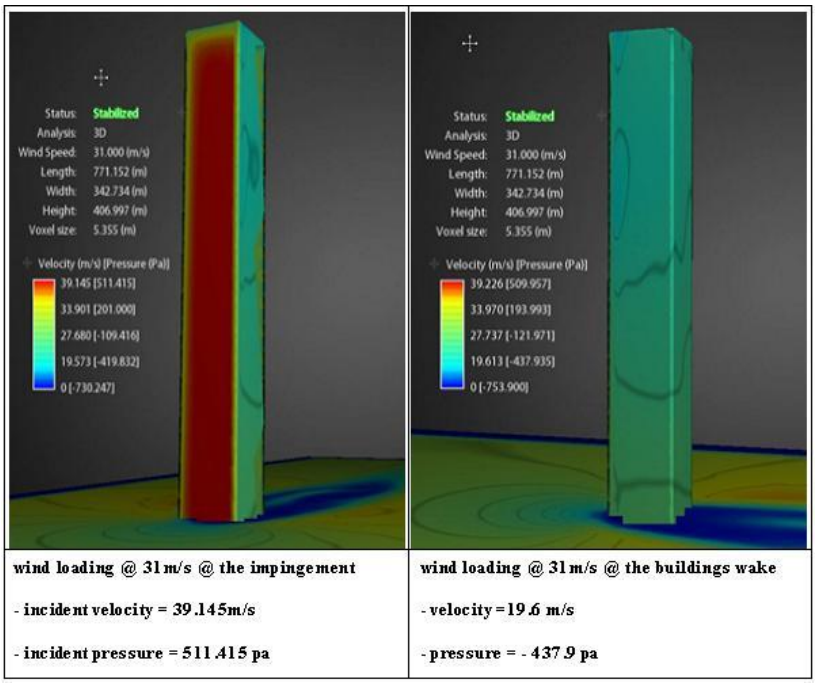


Figure 4.21 Wind loading

(Source: Authors simulation, 2016)

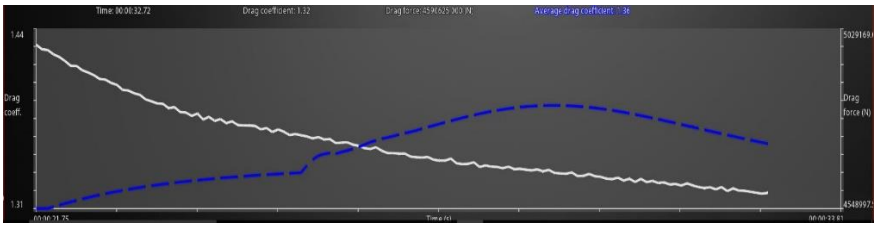


Figure 4.22 Drag coefficient.

(Source: Authors simulation, 2016)

4.6.2.1 Discussion of result

i. From the result obtained in figure 4.21 and 4.22 above is was observed that the incident wind velocity was 39.145m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore this means that staying at the balconies is not advised. However the wind velocity at the wake of the building has a pressure of -437.9pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 39.145 m/s

Incident pressure = 511.415 pa

Drag force = 4590625 N

Drag coefficient = 1.32

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (39.145)^2 x (1.32)

½ x 1.25 x 1532 x 1.32 = 1264.1 pa

1264.1 pa = 1264.1 N/m^2 = 12641.7 N

12641.7 N = 1289 kg. See Table 4.8

Table 4.8 Suitability of glasses

Wind pressure		**1289 kg**	**1289 kg**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.8 above, the wind pressure (1289 kg) exerted on the glass for float and annealed laminated glass has exceeded the allowable load. Whereas for tempered glass, the pressure is just below the allowable load. That means only tempered glass is suitable.

4.7 Curvilinear Form

Figure 4.23 shows the footprint of a curvilinear form, whereas figure 4.24, 4.25 and 4.26 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient respectively.

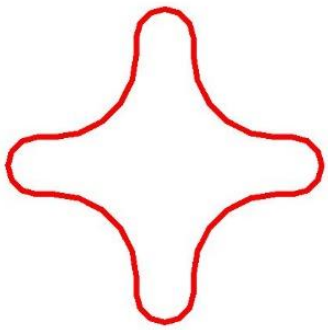


Figure 4.23 Curvilinear form.

(Source: Authors sketch 2016)

4.7.1 Pedestrian wind speed

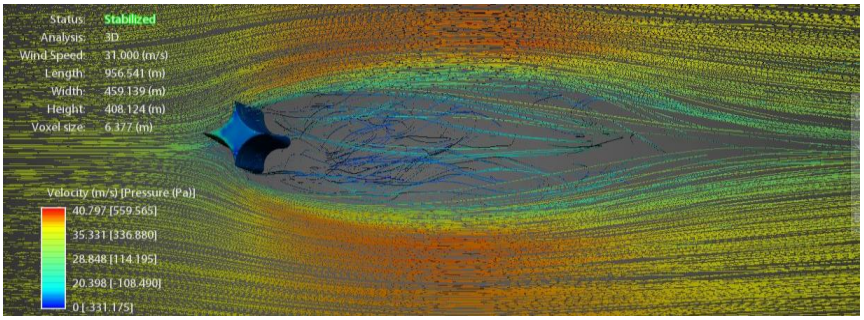


Figure 4.24 Pedestrian wind speed

(Source: Authors simulation, 2016)

4.7.1.1 Discussion of result

From the simulation result in figure 4.24 above it was observed that, the pedestrian wind speed at 31m/s falls between the ranges of 35.3 – 40.797 m/s. therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.7.2 Wind loading and ventilation

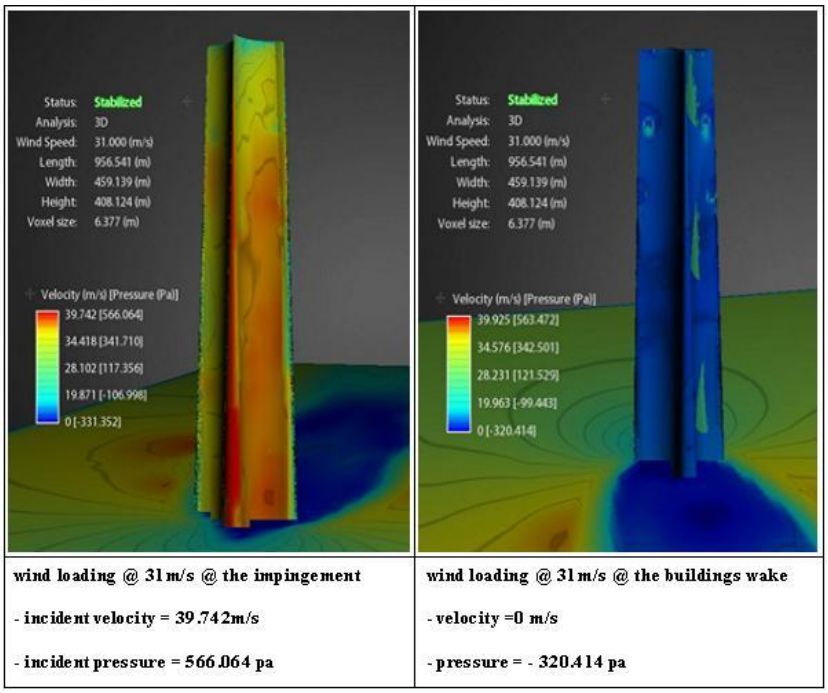


Figure 4.25 Wind loading

(Source: Authors simulation, 2016)

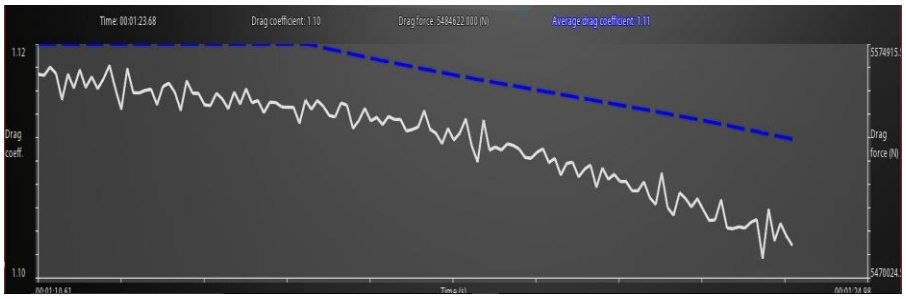


Figure 4.26 Drag coefficient

(Source: Authors simulation 2016)

4.7.2.1 Discussion of result

i. From figure 4.25 and 4.26 above, the incident wind velocity was 39.742 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013). Therefore this means that staying at the balconies is not advised. However the wind velocity at the wake of the building has a pressure of -320.414pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 39.742 m/s

Incident pressure = 566.064 pa

Drag force = 5484622 N

Drag coefficient = 1.1

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (39.742)^2 x (1.1)

½ x 1.25 x 1579.2 x 1.1 = 1085.86 pa

1085.86 pa = 1085.86 N/m^2 = 10,858.56 N

10,858.56 N = 1107.26 kg. See Table 4.9

Table 4.9 Suitability of glasses

wind pressure		**1107.26 kg.**	**1107.26 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.9 above, the wind pressure (1107.26 kg) exerted on the glass for float and annealed laminated glass has exceeded the allowable load. Whereas for tempered glass, the pressure is below the allowable load. That means only tempered glass is suitable.

4.8 Cylindrical form

Figure 4.27 shows the footprint of a cylindrical form whereas figure 4.28, 4.29 and 4.30 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient respectively.

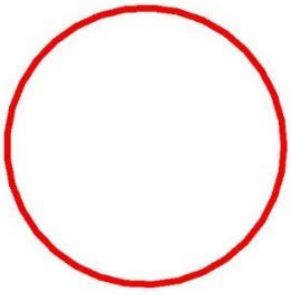


Figure 4.27 Cylindrical form.

(Source: Authors simulation, 2016)

4.8.1 Pedestrian wind speed

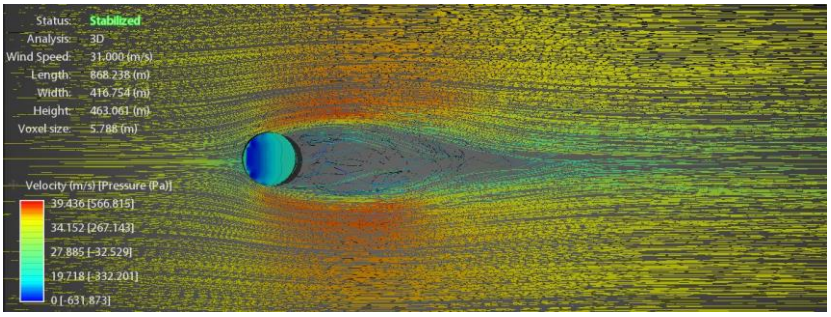


Figure 4.28 Pedestrian wind

(Source: Authors sketch, 2016)

4.8.1.1 Discussion of result

From the simulation result in figure 4.28 above it was observed that, the pedestrian wind speed at 31m/s falls between the ranges of 34.1 – 39.436 m/s. therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.8.2 Wind loading and ventilation

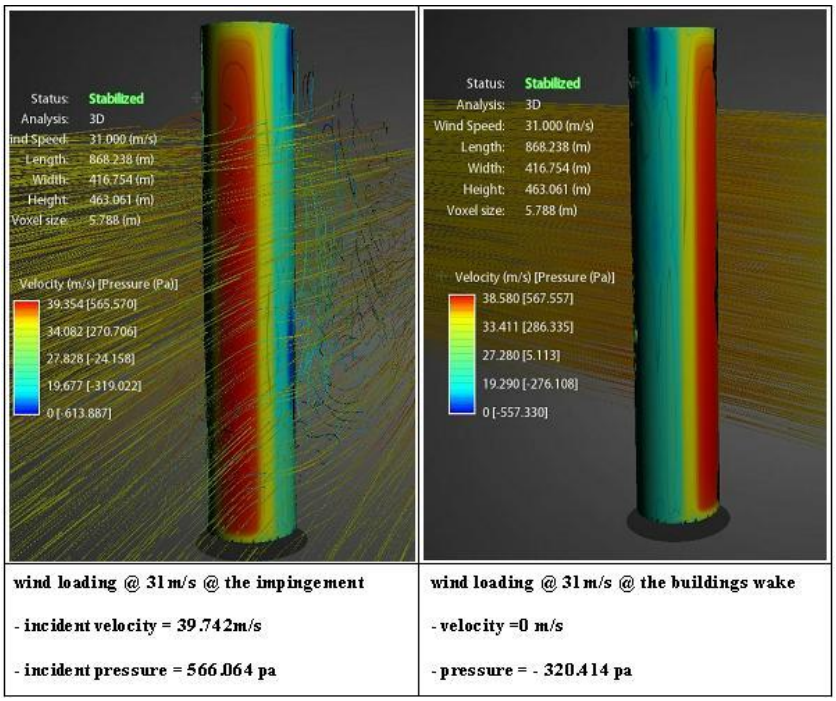


Figure 4.29 Wind loading

(Source: Authors simulation, 2016)

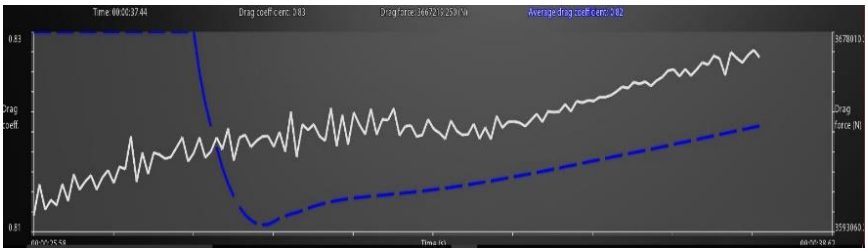


Figure 4.30 Drag coefficient

(Source: Authors simulation, 2016)

4.8.2.1 Discussion of result

i. From the result obtained in figure 4.29 and 4.30 above is was observed that the incident wind velocity was 39.742 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore, this means that staying at the balconies is not advised. However, the wind velocity at the wake of the building has a pressure of -320.414pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 39.742 m/s

Incident pressure = 566.064 pa

Drag force = 3667219.250 N

Drag coefficient = 0.83

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (39.742)^2 x (0.83)

½ x 1.25 x 1579.2 x 0.83 = 819.3 pa

819.3 pa = 819.3 N/m^2 = 8193 N

8193 N = 835.45 kg. See Table 4.10

Table 4.10 Suitability of glasses

wind pressure		**835.45 kg.**	**835.45 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.10 above, the wind pressure (835.45 kg.) exerted on the glass for float and annealed laminated glass has exceeded the allowable load slightly but did not exceed the average maximum failure load. Whereas for tempered glass, the pressure is below the allowable load. That means both glasses are suitable but tempered glass and annealed laminated glass are more suitable.

4.9 Lancet Form

Figure 4.31 shows the footprint of a lancet form whereas figure 4.32, 4.33 and 4.34 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient respectively.

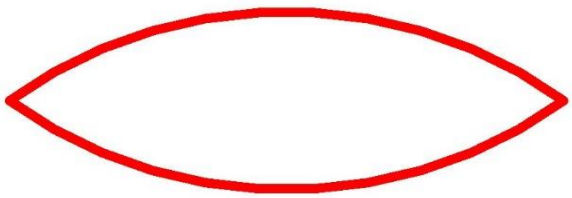


Figure 4.31 Lancet form.

(Source: Authors sketch, 2016)

4.9.1 Pedestrian wind speed



Figure 4.32 Pedestrian wind speed.

(Source: Authors sketch, 2016)

4.9.1.1 Discussion of result

From the simulation result in figure 4.32 above it was observed that, the pedestrian wind speed at 31m/s is 35.6 m/s with the flow passing smoothly over the surface of the Lancet. Therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013).

4.9.2 Wind loading and ventilation

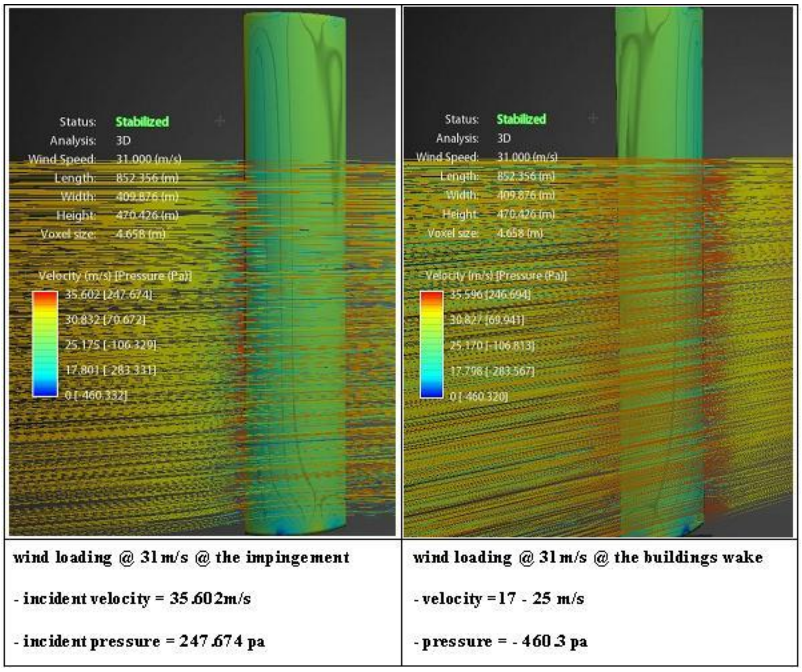


Figure 4.33 Wind loading

(Source: Authors simulation, 2016)

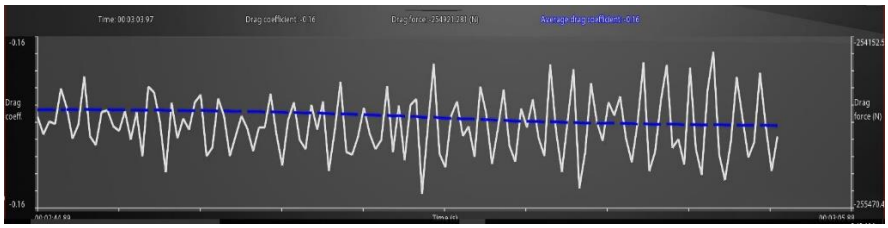


Figure 4.34 Drag coefficient

(Source: Authors sketch, 2016)

4.9.2.1 Discussion of result

i. From the result obtained in figure 4.33 and 4.34 above is was observed that the incident wind velocity was 35.602 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) . Therefore, this means that staying at the balconies is

not advised. However, the wind velocity at the wake of the building has a pressure of – 460.3 pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 35.602 m/s

Incident pressure = 247.674 pa

Drag force = -254921.281 N

Drag coefficient = -0.16

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (35.602)^2 x (-0.16)

½ x 1.25 x 1267.5 x -0.16 = -126.75 pa

-126.75 pa = -126.75 N/m^2 = -1267.5 N

-1267.5 N = -129.24 kg. See Table 4.11

Table 4.11 Suitability of glasses

wind pressure		**-129.24 kg.**	**-129.24 kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.11 above, the wind pressure (-129.24 kg.) is negative. Positive pressure exerts (push) load on the glasses whereas negative pressure exerts a pulling force.

However lancet forms receives more of pulling forces than pushing forces.

4.10 Parallelogram form

Figure 4.35 shows the footprint of a parallelogram form whereas figure 4.36, 4.37 and 4.38 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient respectively.

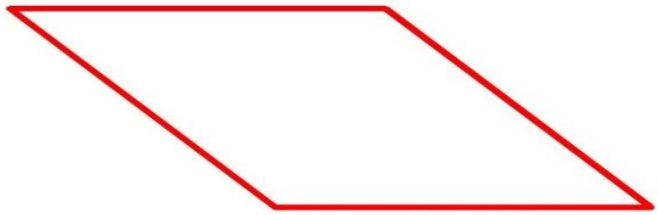


Figure 4.35 Parallelogram form.

(Source: Authors sketch, 2016)

4.10.1 Pedestrian wind speed

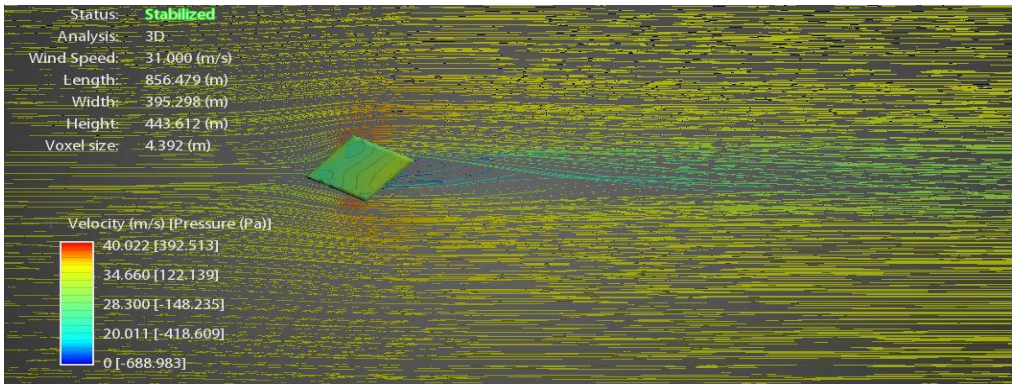


Figure 4.36 Pedestrian wind speed.

(Source: Authors simulation, 2016)

4.10.1.1 Discussion of result

From the simulation result in figure 4.36, the pedestrian wind speed at 31m/s is 40.022 m/s. Therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.10.2 Wind loading and ventilation

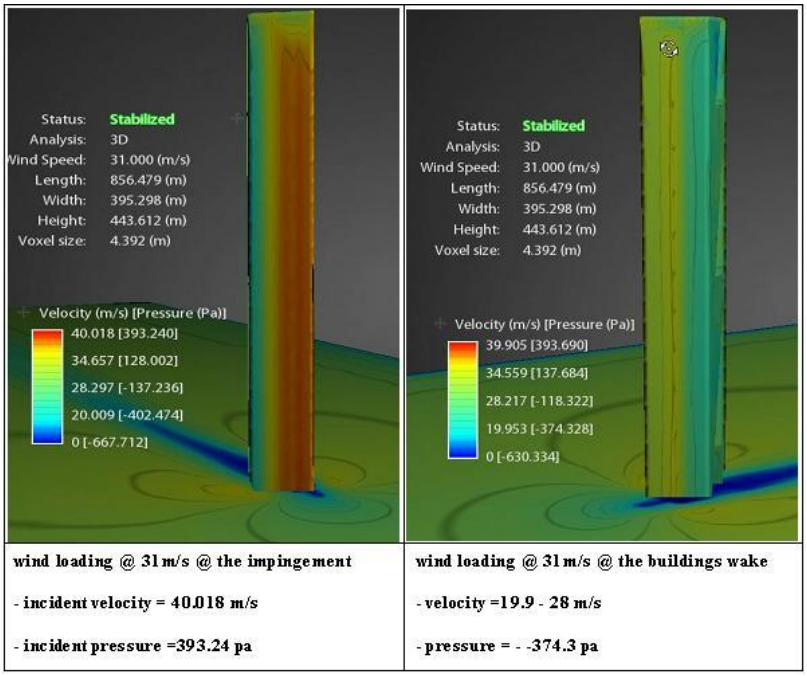


Figure 4.37 Wind loading

(Source: Authors simulation, 2016)



Figure 4.38 Drag coefficient

(Source: Authors sketch, 2016)

4.10.2.1 Discussion of result

i. From the result obtained in figure 4.37 and 4.38 above is was observed that the incident wind velocity was 40.018 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore this

means that staying at the balconies is not advised. However the wind velocity at the wake of the building has a pressure of -374.3 pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 40.018 m/s

Incident pressure = 393.24 pa

Drag force = 1659746.750 N

Drag coefficient = 0.59

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (40.018)^2 x (0.59)

½ x 1.25 x 1601.4 x 0.59 = 590.5 pa

590.5 pa = 590.5 N/m^2 = 5905 N

5905 N = 602.14 kg. See Table 4.12

Table 4.12 Suitability of glasses

wind pressure		**602.14 kg**	**602.14 kg**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.12 above, the wind pressure (602.14 kg.) exerted on the glass for tempered and annealed laminated glass is below the allowable load. For float glass, the pressure is above the allowable load but did not exceed the maximum failure load. That means both glasses are suitable but tempered and annealed laminated glass are more suitable.

4.11 Polygonal form

Figure 4.39 shows the plan of a polygonal form whereas figure 4.40, 4.41 and 4.42 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient.

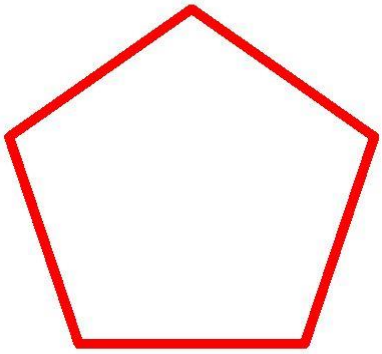


Figure 4.39 Polygonal form.

(Source: Authors sketch, 2016)

4.11.1 Pedestrian wind speed

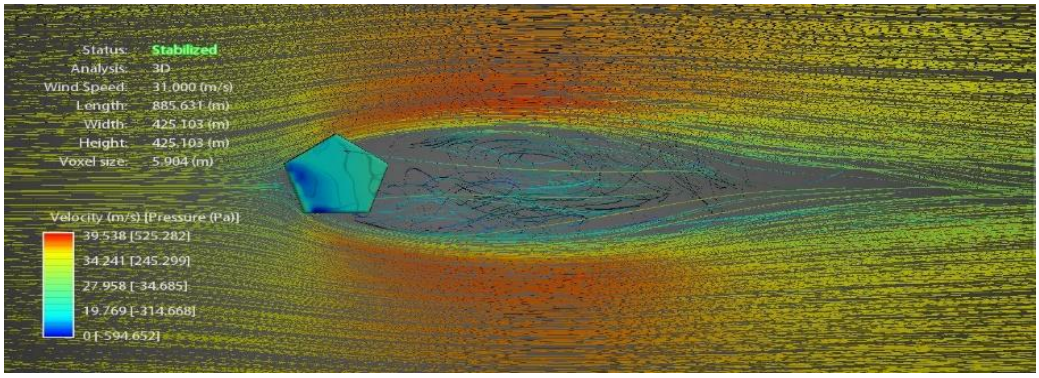


Figure 4.40 Pedestrian wind speed.

(Source: Authors simulation, 2016)

4.11.1.1 Discussion of result

From the simulation result in figure 4.40 above it was observed that, the pedestrian wind speed at 31m/s is 39.538 m/s. Therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013)

4.11.2 Wind loading and ventilation

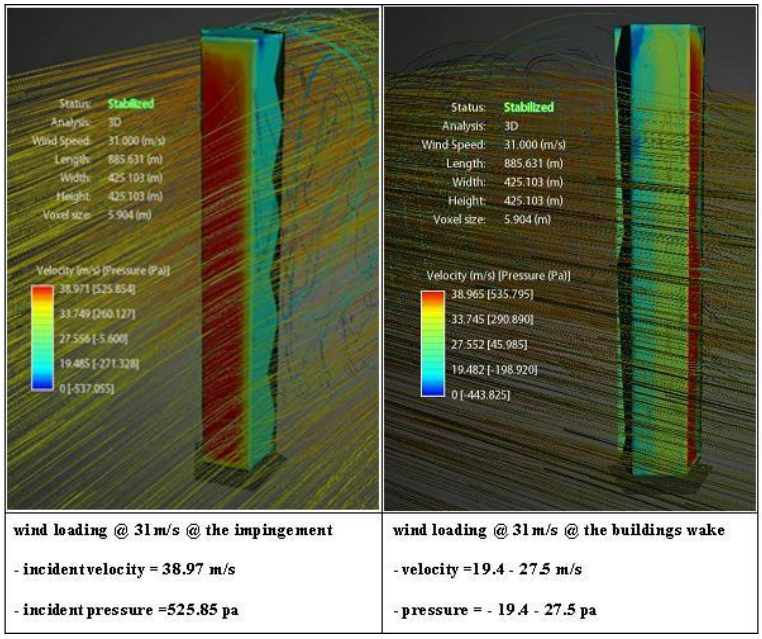


Figure 4.41 Wind loading

(Source: Authors simulation, 2016)

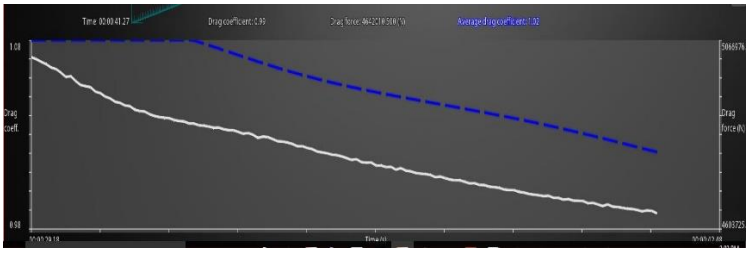


Figure 4.42 Drag coefficient

(Source: Author's simulation, 2016)

4.11.2.1 Discussion of result

i. From the result obtained in figure 4.41 and 4.42 above is was observed that the incident wind velocity was 38.97 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore this means that staying at the balconies is not advised. However the wind velocity at the wake of the building has a pressure of -198.9 pa, this means that high suctions were generated which are dangerous.

ii. Simulation results: incident velocity = 38.97 m/s

Incident pressure = 525.85 pa

Drag force = 4642010.5 N

Drag coefficient = 0.99

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (38.97)^2 x (0.99)

½ x 1.25 x 1518.7 x 0.99 = 939.7 pa

939.7 pa = 939.7 N/m^2 = 9397 N

9397 N = 958.2kg. See Table 4.13

Table 4.13 Suitability of glasses

wind pressure		**958.2kg.**	**958.2kg.**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.13, wind pressure (958.2kg.) exerted on the glass for tempered is below the allowable load. Whereas for float and annealed laminated glass the pressure is above the allowable load. That means both glasses are suitable but tempered glass is more suitable.

4.11.2.2 Discussion of result

From the result above, vortices were generated with a large wake at the lee ward side which may have a dangerous consequence on the building.

4.12 Triangular form

Figure 4.43 shows the footprint of a lancet form whereas figure 4.44, 4.45 and 4.46 below shows simulation results for pedestrian wind speed, wind loading and drag coefficient.

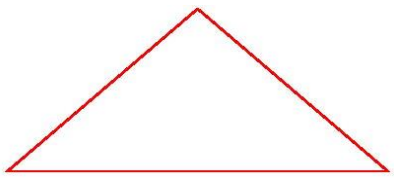


Figure 4.43 Triangular form.

(Source: Author's sketch, 2016)

4.12.1 Pedestrian wind speed

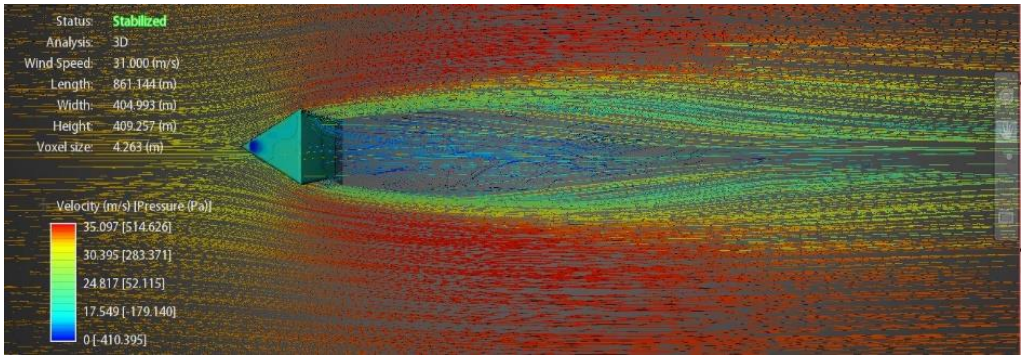


Figure 4.44 Pedestrian wind speed.

(Source: Author's simulation, 2016)

4.12.1.1 Discussion of result

From the simulation result in figure 4.44 above it was observed that, the pedestrian wind speed at 31m/s is 35.1 m/s. Therefore this falls on the range of dangerous class of wind for pedestrian as opined by (Mohamed & John, 2013).

4.12.2 Wind loading and ventilation

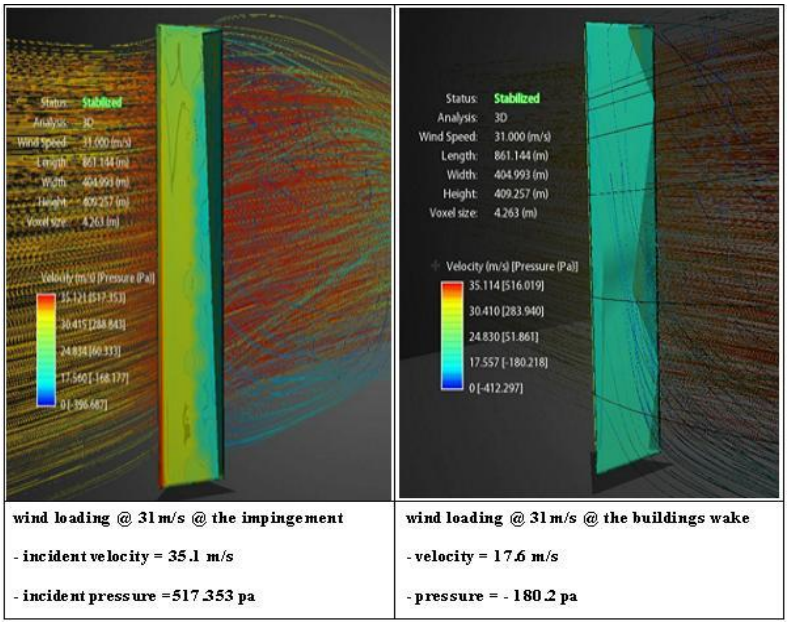


Figure 4.45 Wind loading

(Source: Authors simulation, 2016)

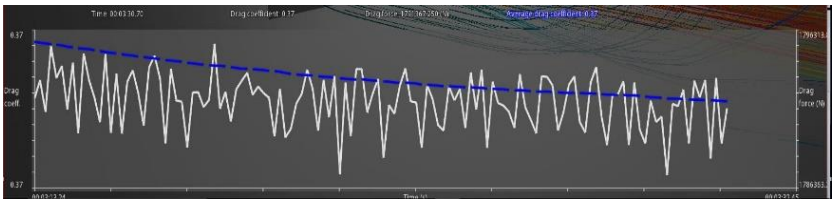


Figure 4.46 Drag coefficient

(Source: Author's simulation, 2016)

4.12.2.1 Discussion of result

i. From the result obtained in figure 4.45 and 4.46 above is was observed that the incident wind velocity was 35.1 m/s with is considered dangerous for walking and not suitable for ventilation through openable windows as opined by (Mohamed & John, 2013) and as shown in his table previously. Therefore, this means that staying at the balconies is not advised. However, the wind velocity at the wake of the building has a pressure of -180.2 pa, this means that high suctions were generated.

ii. Simulation results: incident velocity = 35.1 m/s

Incident pressure = 517.35

Drag force = 1791367.250 N

Drag coefficient = 0.37

Wind Pressure = ½ x (density of air) x (wind speed)^2 x (drag coefficient)

Pressure = ½ x (1.25) x (35.1)^2 x (0.37)

½ x 1.25 x 1232.01 x 0.37 = 284.9 pa

284.9 pa = 284.9 N/m^2 = 2849 N

2849 N = 290.5 kg. See Table 4.14.

Table 4.14 Suitability of glasses

wind pressure		**290.5 kg**	**290.5 kg**
	Thickness (mm)	Average max. failure load (kg)	Allowable load (kg)
Float glass	6	1100	440
Tempered glass	6	3300	1320
Annealed laminated	6 + 6	1800	720

(Source: Kien Safety Glass Sdn Bhd)

From table 4.14 it is observed that the wind pressure (290.5 kg.) exerted on both type of glass is below the allowable load, and that means both glasses are suitable.

4.12.2.2 Discussion of result

From the result above it is observed that, the flow deposits large wake formation behind the building accompanied by free flow of high wind speed with no vortex formation.

5.0 DISCUSSION OF FINDINGS

5.1 Introduction

This chapter display the general discussions of the simulations carried out throughout the research. It also explain the issues relating to the data presentation and analysis which helps in articulating those issues emanating from the analysis with respect to their implications on the subject of investigation.

5.2 General analysis and results

Figure 5.1, 5.2, 5.3 and 5.4 shows the result of simulations in a bar chart. From Figure 5.1 Necom house (rectangle) has the highest pedestrian wind speed followed by the union bank tower (rectangle). The difference between the two towers is the height and building orientation. Cumulatively; the Necom house (rectangle) has the highest pedestrian wind speed of 52m/s and the Lancet form has the least pedestrian wind speed of 35.5m/s.

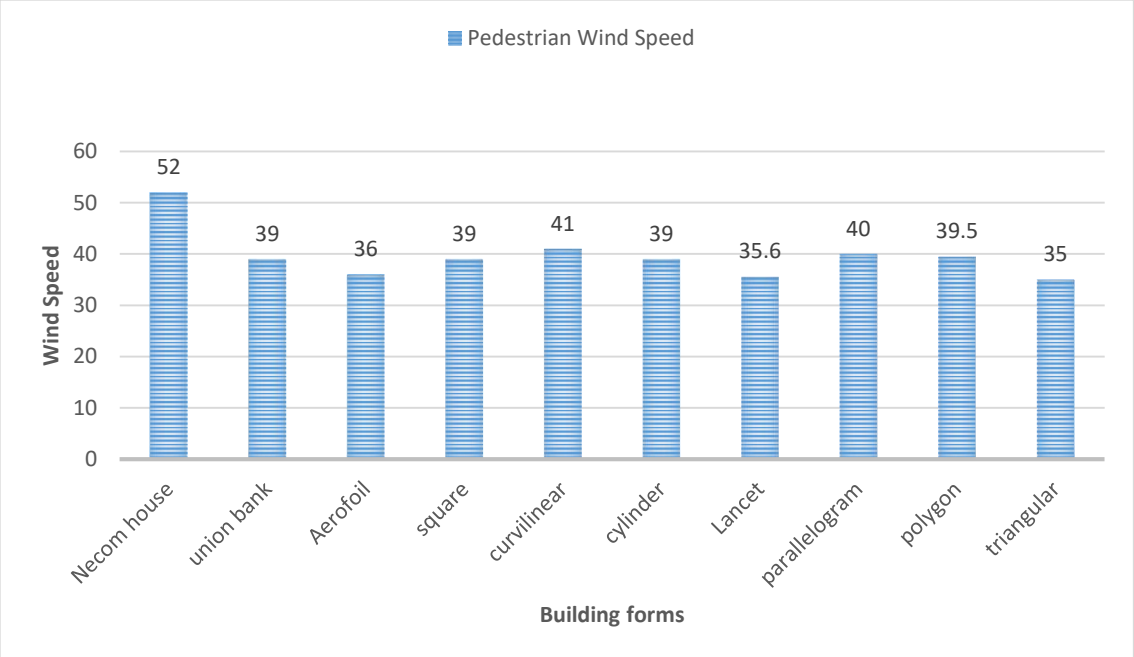


Figure 5.1 Pedestrian Wind Speed

From figure 5.2 below, Necom house (rectangle) has the highest wind loading with a pressure of 631.0pa and Lancet form has the least wind loading with a pressure of 247.67pa. Figure 5.3 shows the result for negative wind loading.

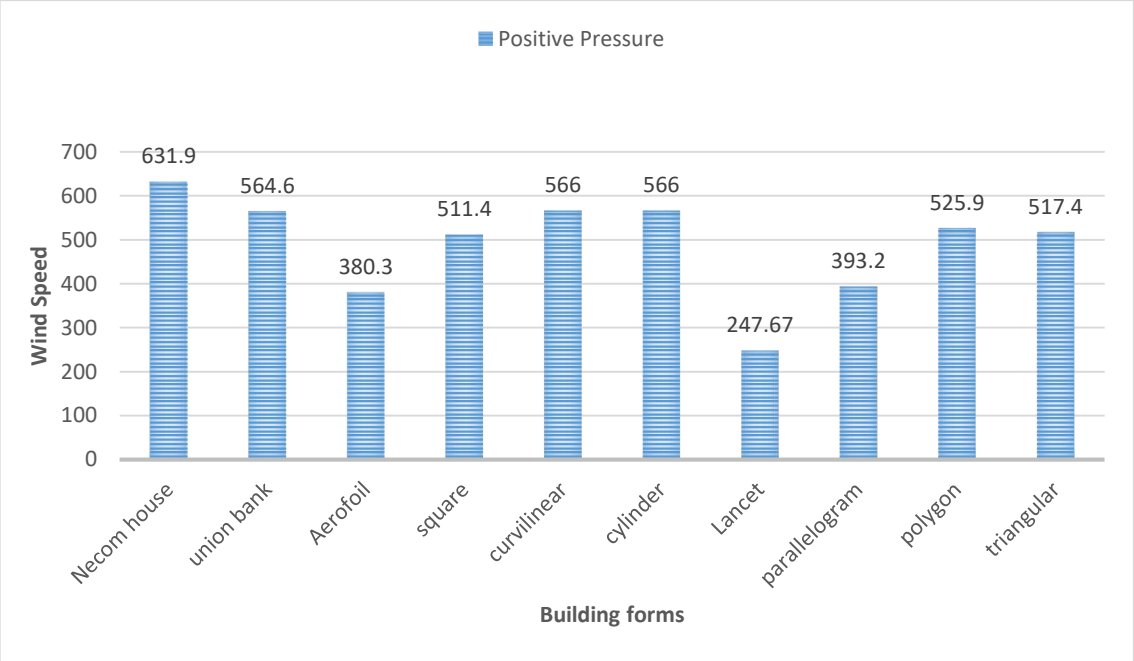


Figure 5.2 +ve Wind loading (push force)

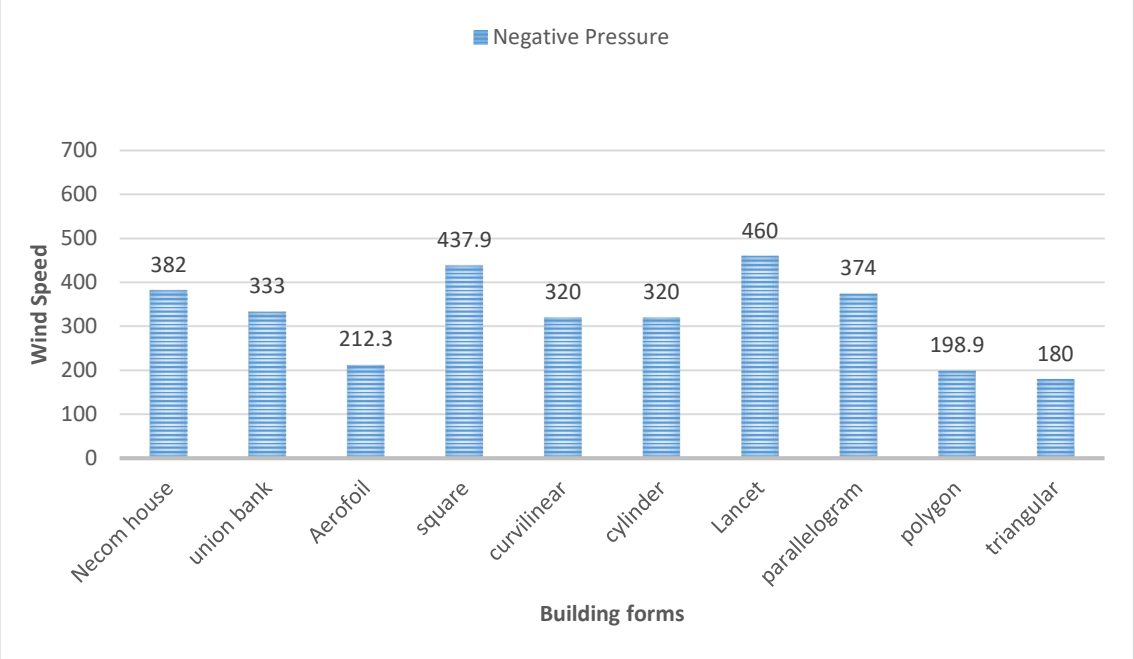


Figure 5.3 -ve Wind loading (pull force)

From figure 5.3 above, Lancet form has the highest negative wind loading with a pressure of -460pa and the triangular form has the least negative pressure of -180pa.

From figure 5.4 below, Necom house (rectangle) has the highest drag coefficient of 1.4 and the Lancet form has the least drag coefficient of -0.16. Higher values indicate a greater resistance to the flow, lower values indicate less wind resistance.

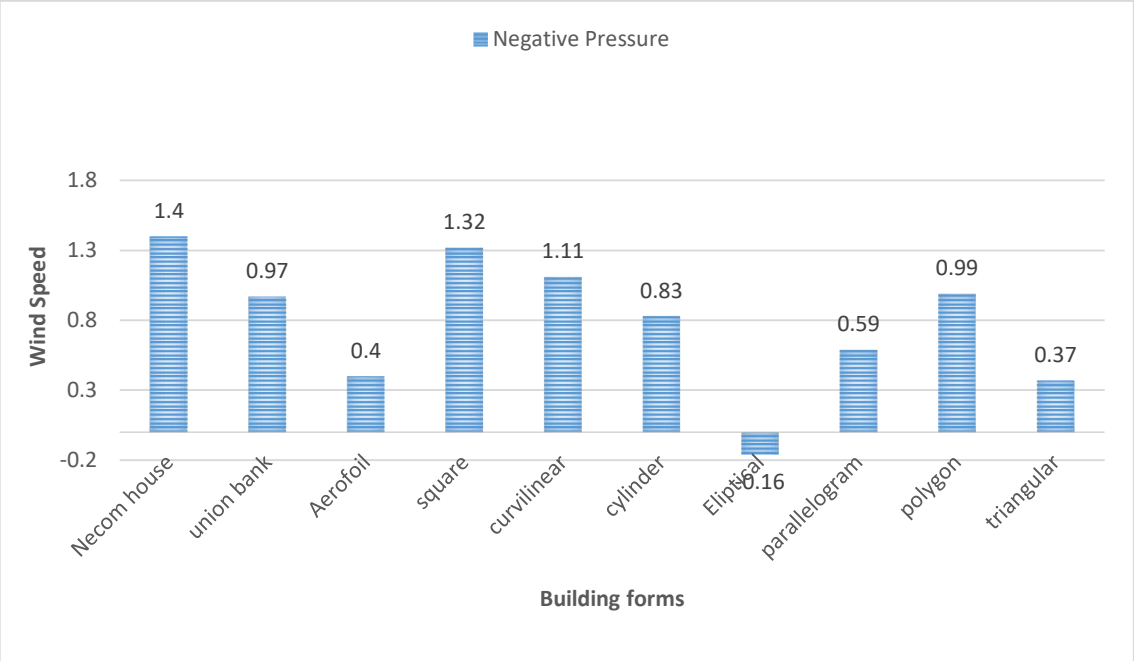


Figure 5.4 Drag Coefficient

5.3 Summary of findings

i. Rectangular building forms has the highest pedestrian wind speed of 52 m/s and lancet form has the least pedestrian wind speed of 32 m/s. Higher wind speed means more danger and should be reduced, by adding some architectural details like tower and podium or changing the orientation.

ii. Rectangular forms has the highest wind loading with a pressure of 631.0pa and Lancet form has the least wind loading with a pressure of 247.67pa. Higher values indicates more danger and vice-versa.

iii. Lancet form has the highest negative wind loading with a pressure of -460pa and the triangular form has the least negative pressure of -180pa. Higher negative pressure indicates more suction with is equally dangerous as positive pressure.

iv. Rectangular forms has the highest drag coefficient of 1.4 and the Lancet form has the least drag coefficient of -0.16. Lower values indicate more stability and vice versa.

v. Both building forms have an incident wind velocity which is too dangerous to have an openable window.

vi. Natural ventilation can be achieved passively on both forms by adding little modification to the form as seen from the simulations of this research.

vii. The high speed exhaust air leaving the ventilation shaft of the Lancet has a speed range of 32 – 36m/s and a pressure of 615pa, this means that, the pressure is enough to cause induced pressure ventilation inside the building whereas the wind speed has the magnitude required for the operation of wind turbines.

6.0 THE SITE

6.1 Eko Atlantic

Eko Atlantic city in general is an already planned city that has been divided into land use developments, the master plan has been divided into four type of developments: financial hub, commercial development, residential development and touristic development as shown in figure 6.1 below. One of the major aims for the development of Eko Atlantic city was to promote tourism, reclaimed lost land, and to generate revenue for the state. Among all the four type of development mentioned above touristic development appeared to be a more perfect site to be used for a mix-use development.

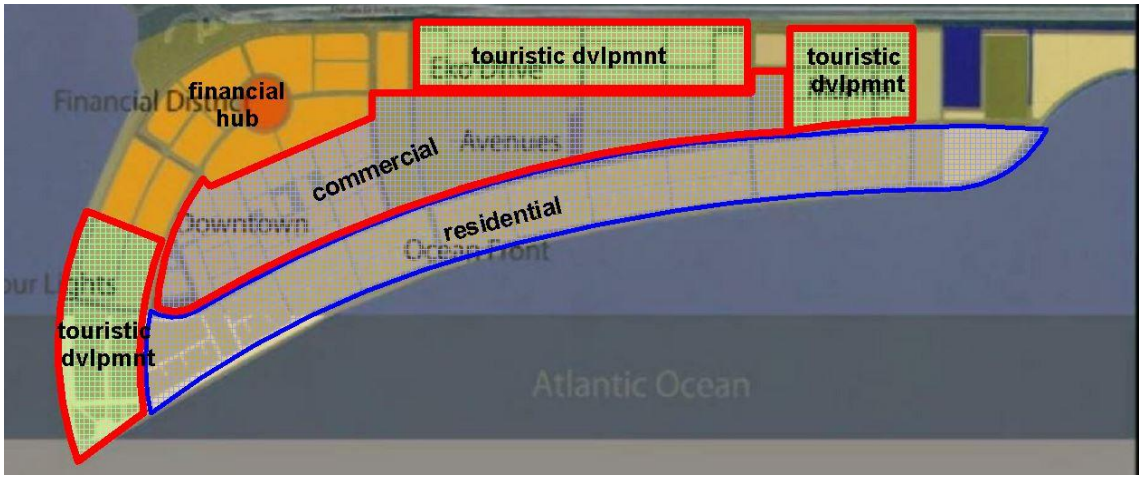


Figure 6.1 Eko Atlantic city master plan.

(Source: South Energyx Nigeria Limited, 2013)

6.2 Site Selection Criteria

Three different site were selected for the project as shown in figure 6.2 below,



Figure 6.2 Eko Atlantic city master plan.

(Source: South Energyx Nigeria Limited, 2013)

The following under listed criteria were used to weigh the suitability of each of the site and thus the most appropriate site was selected as shown in table 6.1 below.

i. Site location/Accessibility
ii. Proximity to leisure and recreation features
iii. Vicinity to work areas.
iv. Land use compliance
v. Suitability
vi. Size and terrain of site
vii. Location away from the loud noises of township life
viii. Availability of services
ix. Availability of social amenities

Table 6.1 Site selection criteria

CRITERIA	SITE A	SITE B	SITE C
Site Accessibility By the public	5	5	5
Proximity to business areas and city features	4	3	4
Vicinity to work areas	4	2	3
Land use compliance	5	5	5
Location away from the loud noises of unnecessary sources	2	2	5
Size and terrain of site,	3	4	4
Suitability	3	3	4
Total	26	24	30

(Source: Author 2016)

Weighing scale: Excellent (5), Very good (4), Strong (3), Weak (2), Very Weak (1).

From Table 6.1 site (c) appeared to be more suitable for this research.

6.3 Site Analysis

This section gives the general overview and history of the climate and whether information of the selected site. The physical, climatic, and general features of the site were analyzed in order to identify the possible opportunities that was utilized for a better design and also took note of the threats and possible measures to reduce their effect to the building. The following are features that were noted during analysis of the site

6.3.1 Site location

The site is located at the Eko Atlantic city in Lagos state of Nigeria, the site lies on a coordinates of latitude 6° 23'59.41" N and longitude 3° 24'15.81" E as shown in figure 6.3 below.

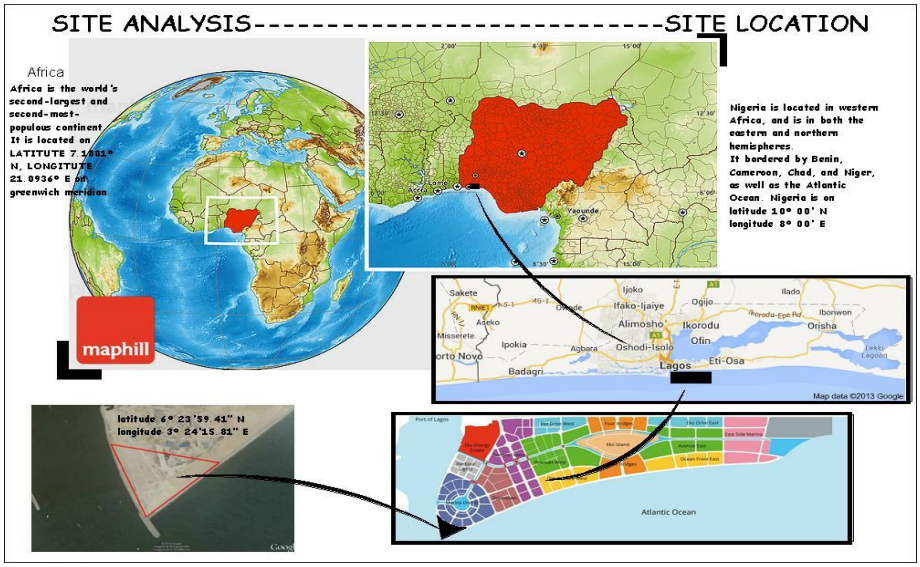


Figure 6.3 Site location

6.3.2 Topography

The site is relatively flat with a gentle slope of 0.5%. as shown in figure 6.4 below.

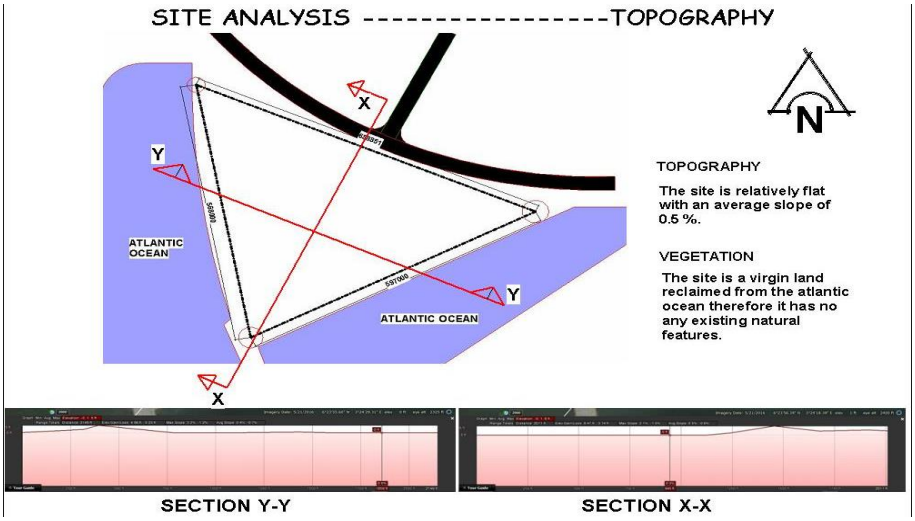


Figure 6.4 Topography

6.3.3 Services

Across Eko Atlantic, all electricity and telecoms utility services are being installed below street level as shown in figure 6.5 below. Development continues on schedule with ductwork for telecoms services currently being laid in Eko Boulevard.

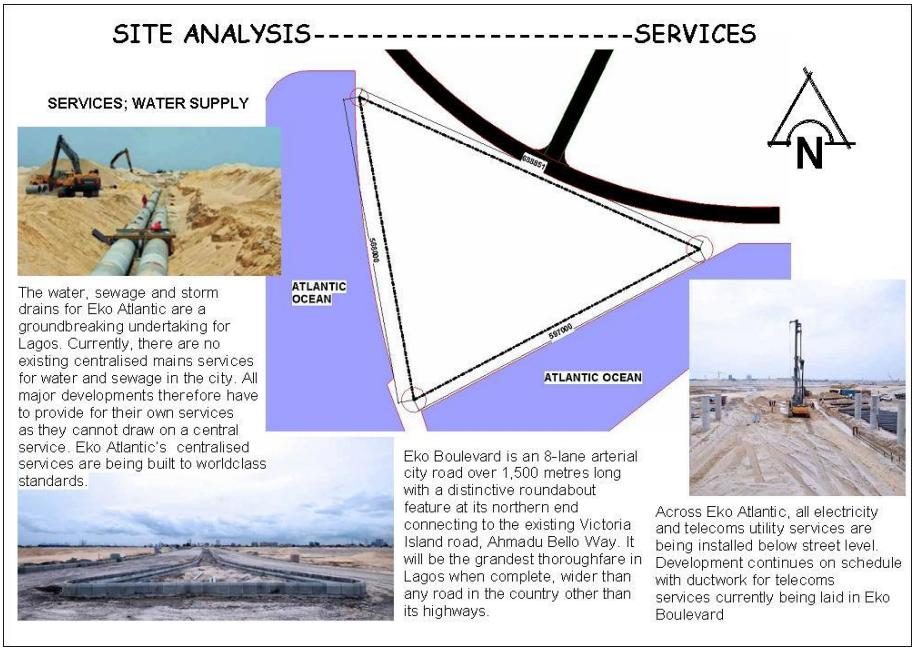


Figure 6.5 Services

6.3.4 Climatic Analysis

The climate in Nigeria typically varies; equatorial in south, tropical in center, arid in north. The terrain: southern lowlands merge into central hills and plateaus; mountains in southeast, plains in north.

6.3.5 Historical Monthly Averages for April

The information presented below gives detailed historical monthly average weather conditions along with exceptional weather occurrences. To maintain relevance to current weather trends the displayed information has been calculated using data collected over

the past two decades. The climate profile is taken from closest available data source to Lagos.

6.3.5.1 Temperature

Throughout the month of April daytime temperatures will generally reach highs of around 32°C that's about 89°F. At night the average minimum temperature drops down to around 26°C, that's 79°F. In recent times the highest recorded temperature in April has been 37°C that's 98°F, with the lowest recorded temperature 16°C, about 61°F as shown in figure 6.6 below

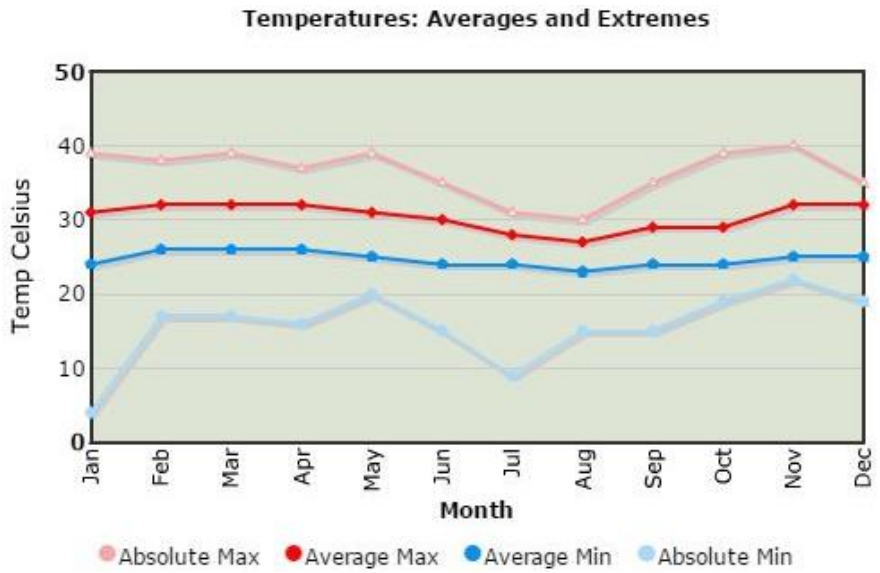


Figure 6.6 Temperature: Averages and Extremes

6.3.5.2 Relative Humidity

The average daily relative humidity for April is around 82%.

6.3.5.3 Heat Index

The Heat Index is a measure of how hot it feels when relative humidity is added to actual air temperature. From this a comfort level is calculated providing categories on how heat conditions might adversely affect someone.

6.3.5.4 Comfort Levels

Given average maximum temperatures and humidity levels you can expect dangerous heat conditions. Sunstroke, muscle cramps and heat exhaustion are likely. Heatstroke is possible with prolonged exposure and/or physical activity (see heat index for more information).

6.3.5.5 Precipitation

The average monthly amount of precipitation has been recorded at around 135 mm, that's 5 inches. Throughout the month you can expect to see rain or drizzle falling on 8 days of the month as shown in figure 6.7 below.

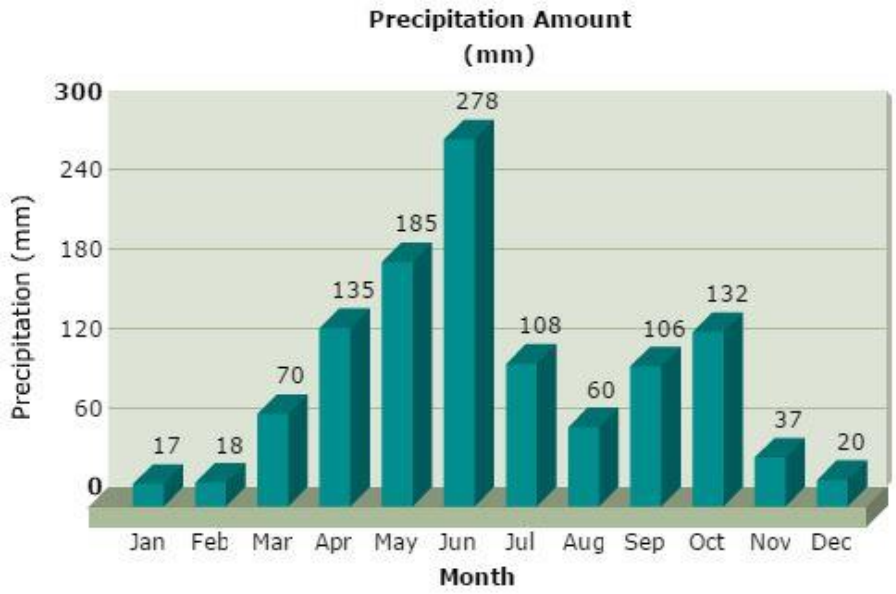


Figure 6.7 Precipitation Amount

6.3.5.6 Estimated Hours of Sunshine per Day

The sunshine hours was calculated per day using past forecast data. For April expect the sun to shine for an average of 9 hours per day. This represents the average number of hours in the daytime that the sun is visible and not obscured by cloud e.g. the average

number of hours the sun is actually out and shining. Note the hours of sunshine per day using past forecast data, not observation data, thus it is an estimate and not actual.

6.3.5.7 Wind

The average daily wind speed in April has been around 15 km/h, that's the equivalent to about 10 mph, or 8 knots. In recent years the maximum sustained wind speed has reached 111 km/h, that's the equivalent of around 69 mph, or 60 knots as shown in figure 6.8 below.



Figure 6.8 Wind Speed (km/h)

6.3.5.8 Fog

On average the month of April is not affected by foggy conditions.

6.3.5.9 Swimming and Water Temperature

The temperature of water an individual will feel comfortable in is very much personal preference. What feels unbearably cold to one person for a swim might be fine for another. In April, for the nearest coastal location, the temperature of the sea averages around 29°C, that's 84° Fahrenheit. Our index indicates for swimming in this is considered very warm

and would be enjoyed by all. With this temperature you can stay active in the water for extended periods of time without feeling uncomfortable see figure 6.9.

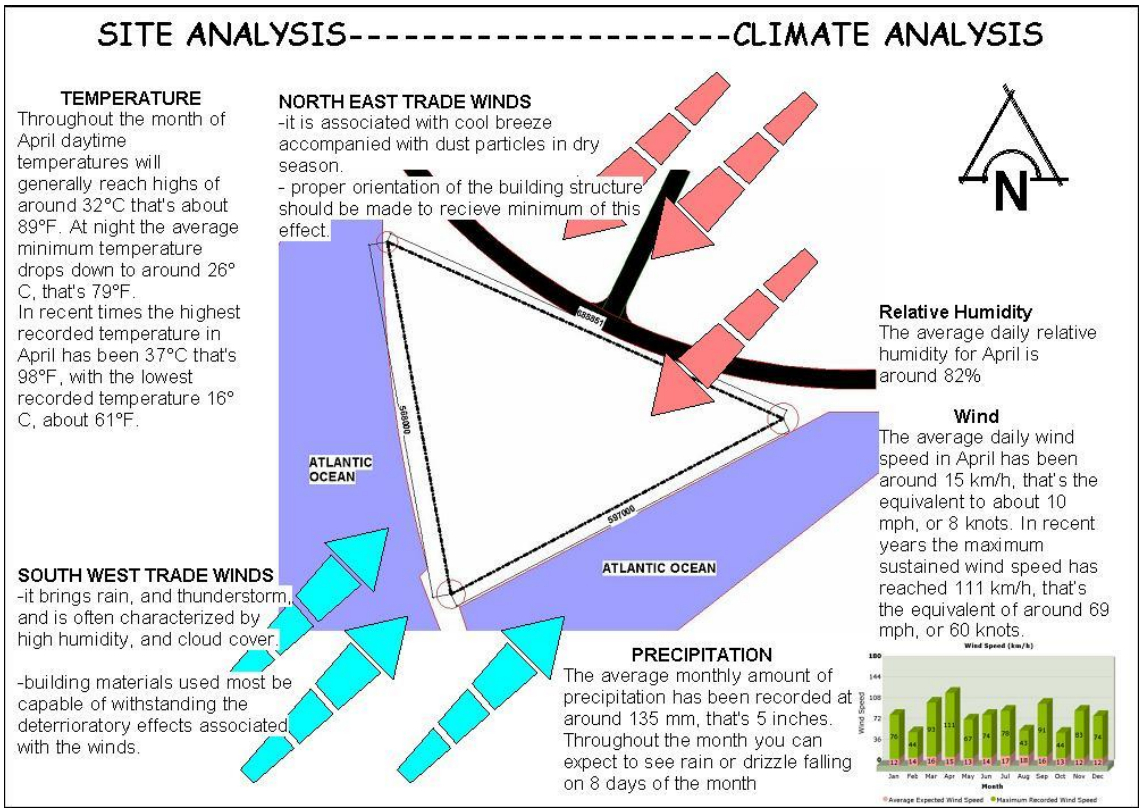


Figure 6.9 Climate Analysis

7.0 DESIGN REPORT

7.1 Design Brief

From inception, Eko Atlantic city was design to recover the loss land from the Atlantic Ocean and to boost tourism for the state and the nation. The master plan was divided into four type of developments: financial hub, commercial development, residential development and touristic development. This research adopts its site from the touristic development, several proposals were provided to enhance the tourist site therefore; this research proposed a mixed-use high rise development to house; shopping malls, hotels, residential spaces, observation decks, and office spaces. The mixed-use was also designed to be an icon or signature building for the nation as it is expected that the tallest building in Africa to emanate from that site.

7.2 Concept Development

The concept adopted for this design was a product of careful analysis of different high rise building forms in respect to wind effects, and Lancet form appeared to be the verdict se figure 7.1 below. However, the Lancet form was eventually chosen for this research, further simulations were carried out to improve the aerodynamic nature of this form.

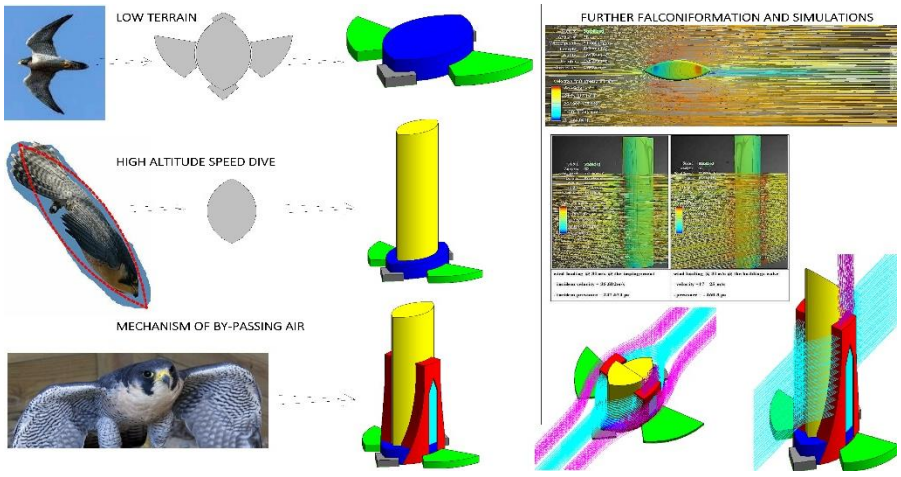


Figure 7.1 Concept development

7.3 Source of Inspiration.

Since the beginning of technology man has been known for mimicking nature as a solution to his problem, however this research is no different. For decades, third generation skyscrapers were designed to be covered and sealed with glass panels as the latest trend in technology, and the only reason why these buildings were sealed is because of the high wind speed at higher altitudes, this particular issue of wind rendered the operation of this buildings very expensive.

However, the solution to this problem has been solved in the anatomy and flight dynamics of the world fastest animal, the (peregrine falcon). Peregrine falcon dives at a speed of over 386.2 km/h, normal bird travelling at this speed will eventually die because it will not be able to breathe, which is exactly similar to the problem of our skyscrapers of today. The Peregrine Falcon maintains a one-way flow of air so that it can breathe while flying. This system is much more efficient than the more common two-way flow of air. However, this system was adopted to solve the problem of natural ventilation in high rise buildings.

7.4 Floor Layout

The proposed building is made of 9 tiers which are further divided in to 65 levels.

Basement……mechanical floor

Ground floor – 5^{th} floor…….shopping mall

6^{th} – 25^{th} floor……hotel

26^{th} floor……mechanical floor

27^{th} floor ……...refuge floor

28^{th} – 33^{rd} floor…….1&2 bedroom residential

34^{th} – 37^{th} floor…….3 bedroom residential.

38^{th} – 41^{st} floor……..residential duplexes

42^{nd} floor…….mechanical floor

43^{rd} floor…….helipad, observation deck, sky lobby

44^{th} – 53^{rd} ……...office spaces

54^{th} floor…….mechanical floor

55^{th} – 64^{th} floor……..office spaces

65^{th} floor…….observation deck/ last floor

7.5 Strategies Adopted to Minimize the Effects of Wind on the Building Form

The following strategies were employed to minimize the effect of wind on the building form.

7.5.1 Building form

The building form chosen for this research was a product of simulation analysis of different high rise building forms and elliptical form appeared to be the verdict of the analysis, and therefore eventually chosen.

7.5.2 Building Orientation

To minimize this effects the longer side of the building was aligned along the south west and north east. This orientation makes it possible to capture the wind and harnessed it for natural ventilation purposes and for generation of electricity.

7.5.3 Addition of ventilation shaft to the building form

A specially designed ventilation shaft inspired by a diving falcon was designed and introduced to the building form, this ventilation shaft was used to introduce natural ventilation by induction to the building, however the excess air leaving the shaft was used to power wind turbines for generation of electricity. The image below shows the working process of this ventilation shaft as shown in figure 7.2 below..

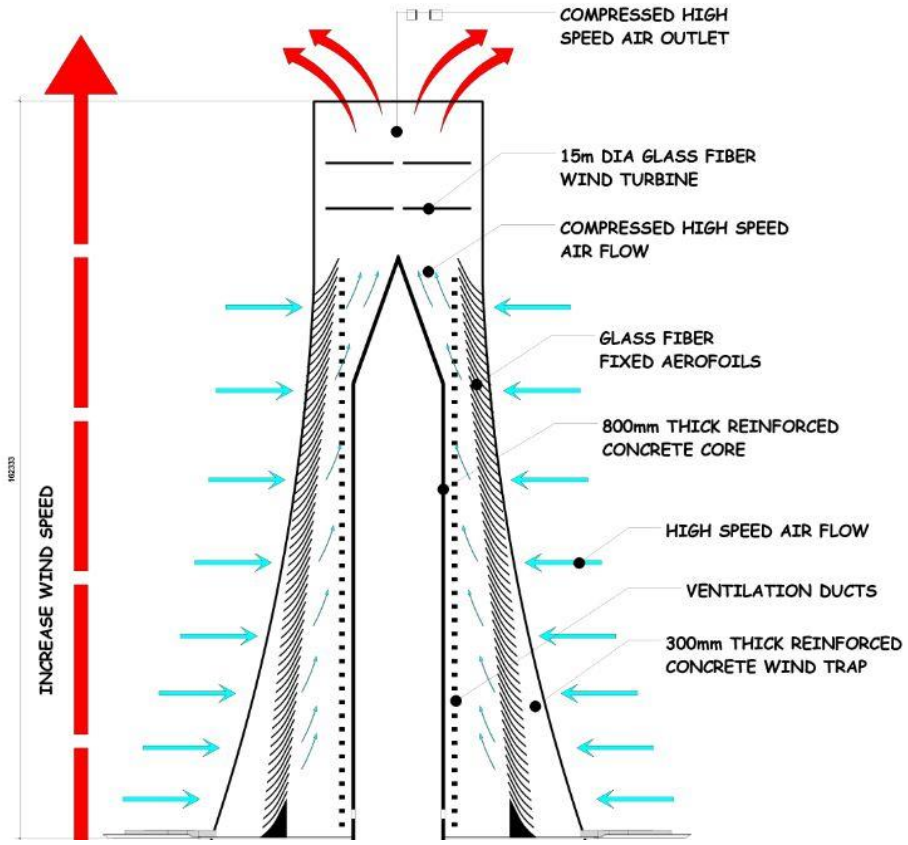


Figure 7.2 Ventilation shaft

Figure 7.3 and 7.4 shows the simulated result and target wind speed for the verification of the workability of the ventilation shaft.

7.5.4 CFD Simulation for the experimental verification of the workability of the ventilation shaft

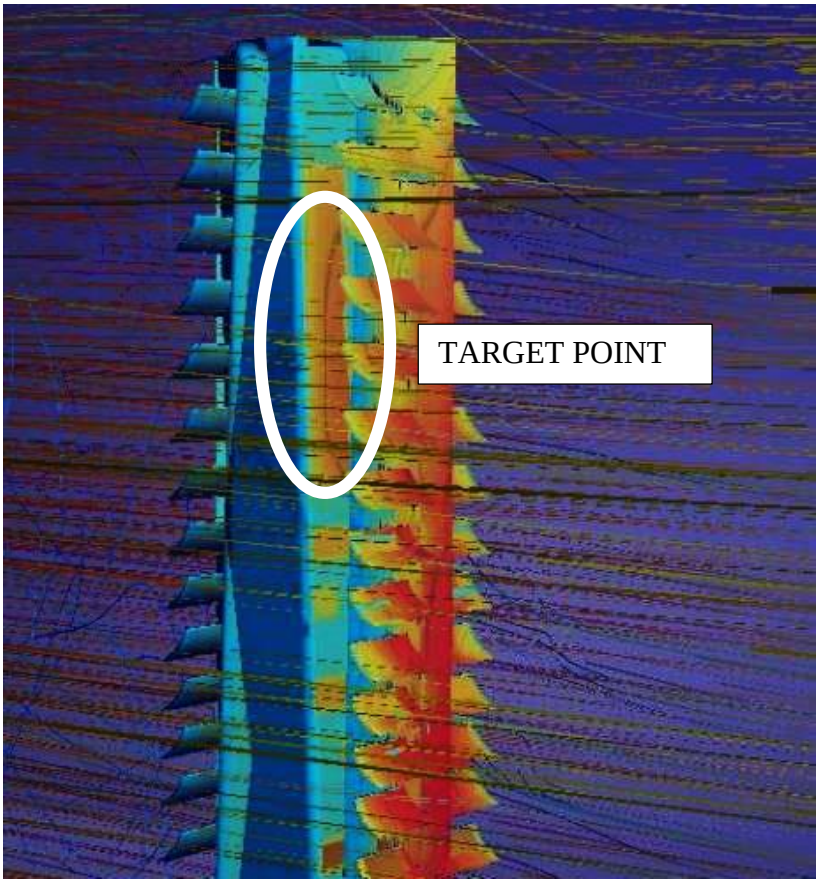


Figure 7.3 CFD Simulation

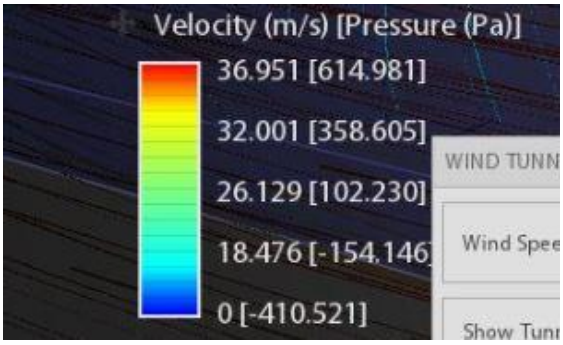


Figure 7.4 CFD Simulation result

From the simulation above it is observed that the wind speed living the ventilation shaft falls within the range of 32 to 36.9 m/s. however from literature review a wind speed if 15m/s is required to turn a wind turbine, therefore this proves that the wind speed living the shaft has enough magnitude to turn a wind turbine and the pressure of 614 is enough to cause ventilation by induction in the building.

8.0 CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

The research has successfully established a distinction on different high rise building forms in order of effects they receive from high wind speed, and how this wind effects can be minimized. The verdict appears to be lancet form, in the process of achieving the aim of this research and to minimize wind effects, a specially designed ventilation shaft was used, which works on the basis of ventilation by induction. This shaft also utilizes the exhaust air for the generation of electricity, to achieve maximum use of this shaft, the building should be oriented with the shaft facing the south west and north east direction.

8.2 Contribution to knowledge

i. By designing a high rise building with the ability to maneuver high wind speed around its geometry for other useful purposes, thus minimizing the wind effects greatly.

ii. The design of a ventilation shaft used to induce natural ventilation

iii. The ventilation shaft introduced also served as a means of improving energy efficiency by way of harnessing the exhaust air leaving the shaft for electricity generation.

iv. The use of the ventilation shaft also may reduce sick building syndrome.

8.3 Recommendations

i. Architects should search for more alternative ways of providing natural ventilation in High rise buildings

ii. Aerodynamic building forms tends to have higher resistance to wind than normal building forms, therefore architects should consider them more.

iii. When designing for natural ventilation in high rise buildings, orientation is one of the most important thing to consider.

8.4 Areas of Further Research

1. Testing the framework developed in this study in other geographical locations with similar or worst environmental conditions.
2. The application of the ventilation shaft used in this research in other building forms to study their response
3. Research to be carried out to find other alternative and passive means of creating natural ventilation in high rise buildings

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cad=rja&uact=8&ved=0ahUKEwjRls-_jN3OAhXCWRQKHUUoDS8QFghMMAs&url=http://www.ksg.com.my/download/wind_pressure.pdf&usg=AFQjCNEhHKpVkai3Sr5ZDWLzv6QB2aswMw&sig2=Myiq2VJtcGRf2a8jOxoCUw

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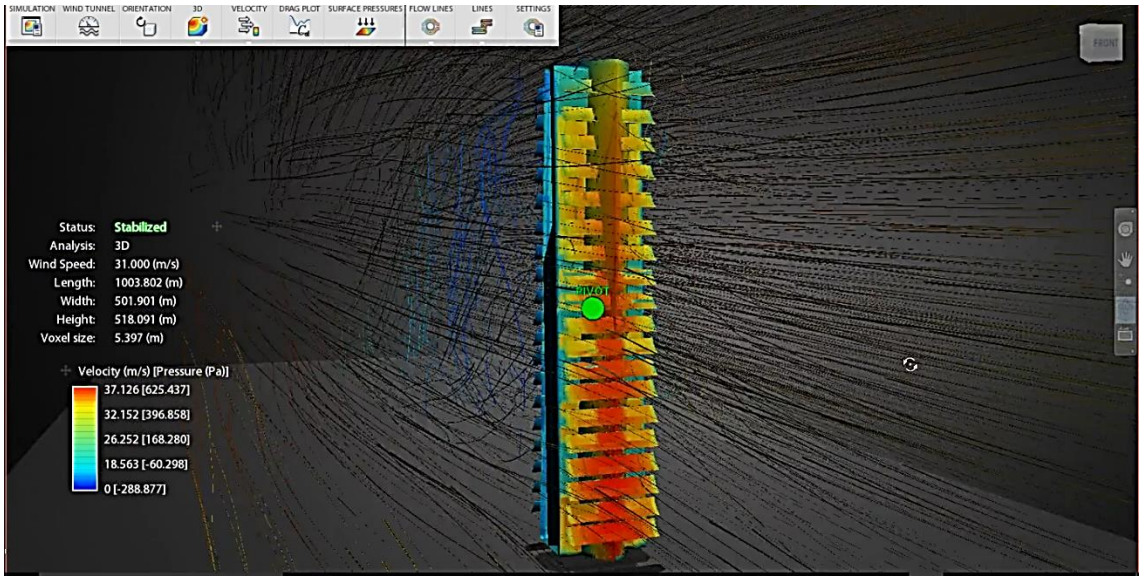
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APPENDICES

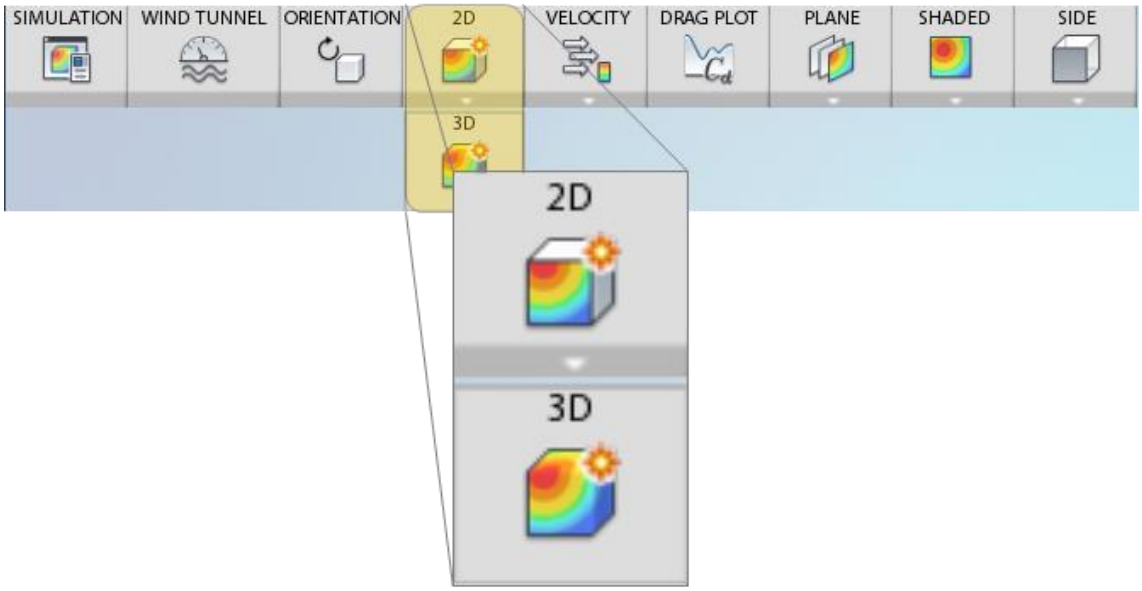
APPENDIX I

Project information of the baseline model in flow design



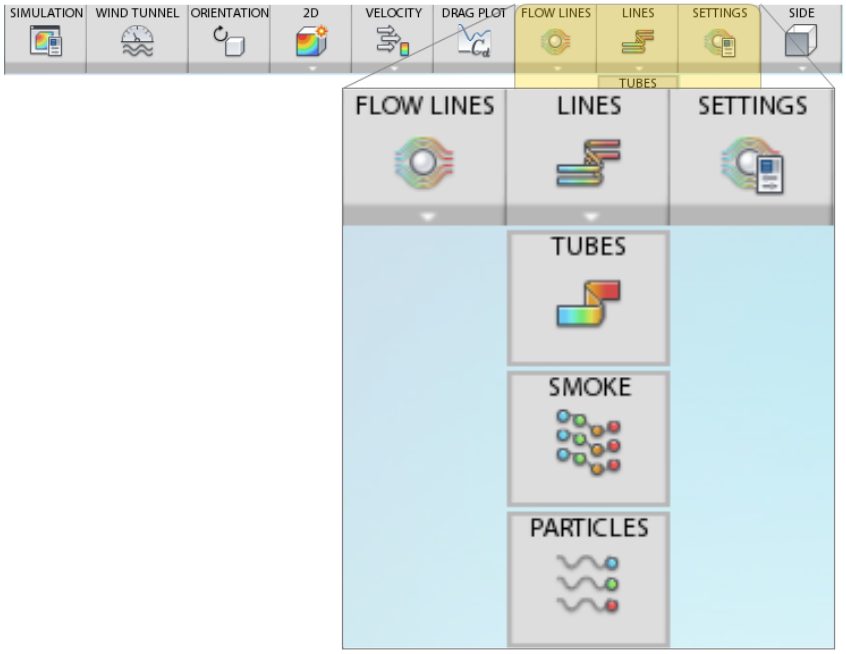
APPENDIX II

General setting for 2d or 3d simulation.



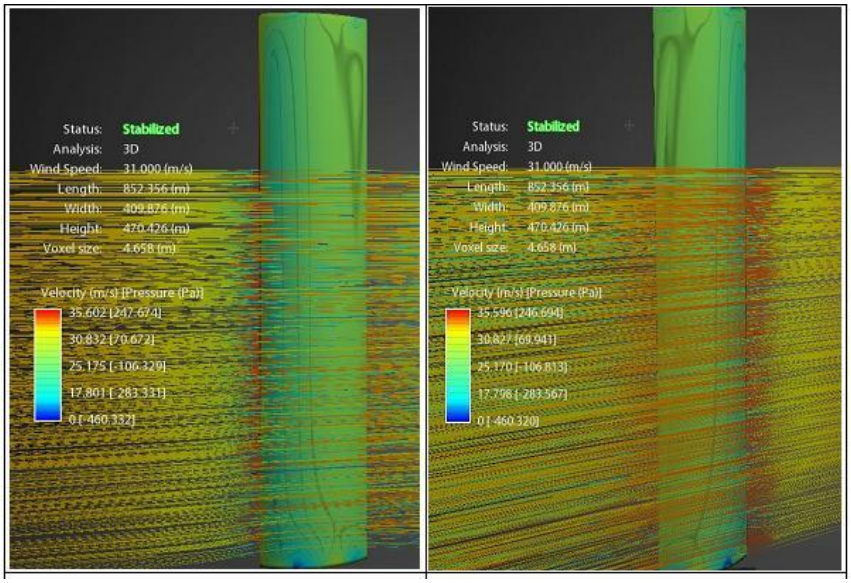
APPENDIX III

Main settings for flow lines, lines, tubes and smoke simulations



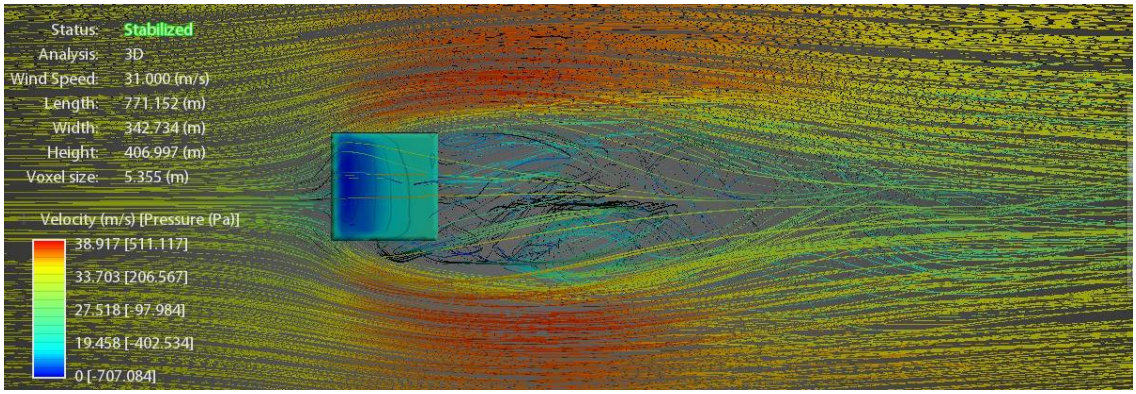
APPENDIX IV

Flow line simulation of elliptical form



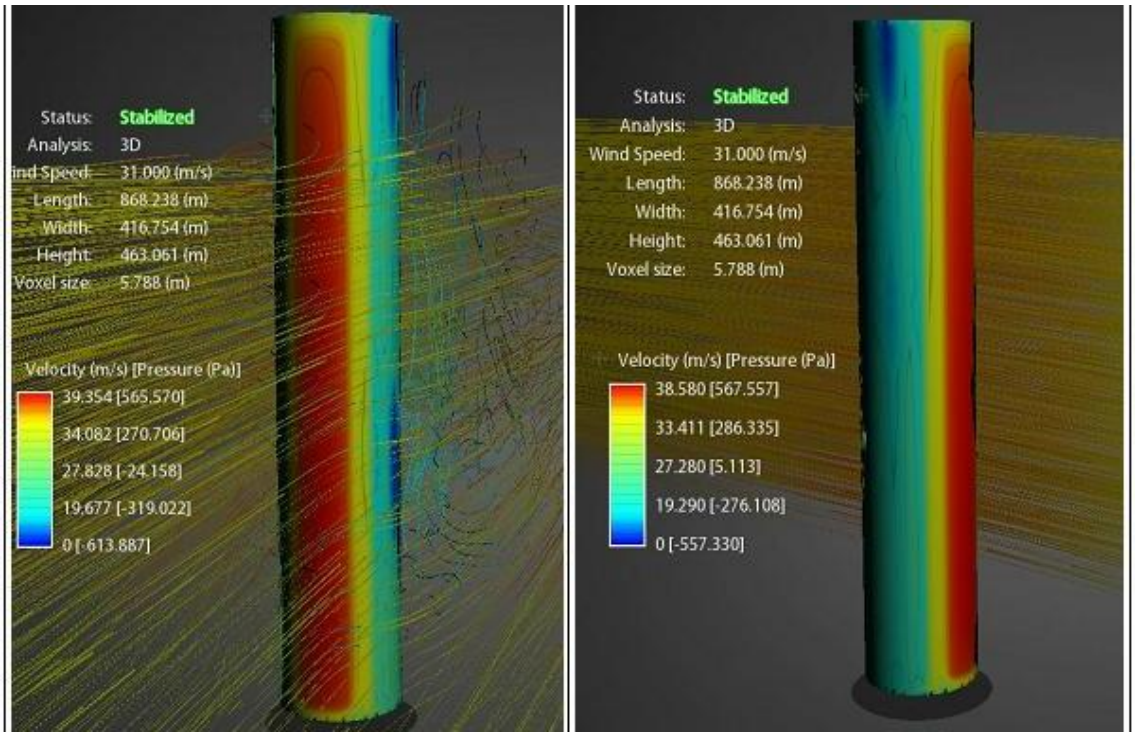
APPENDIX V

Flow pattern on cuboid form



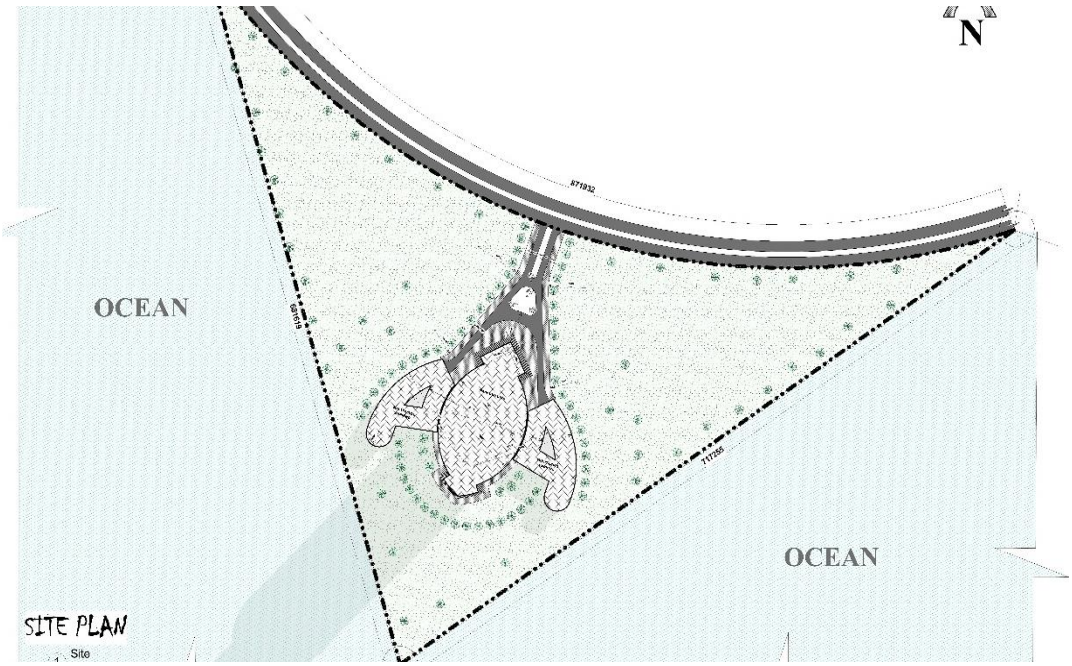
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Flow pattern on cylindrical form



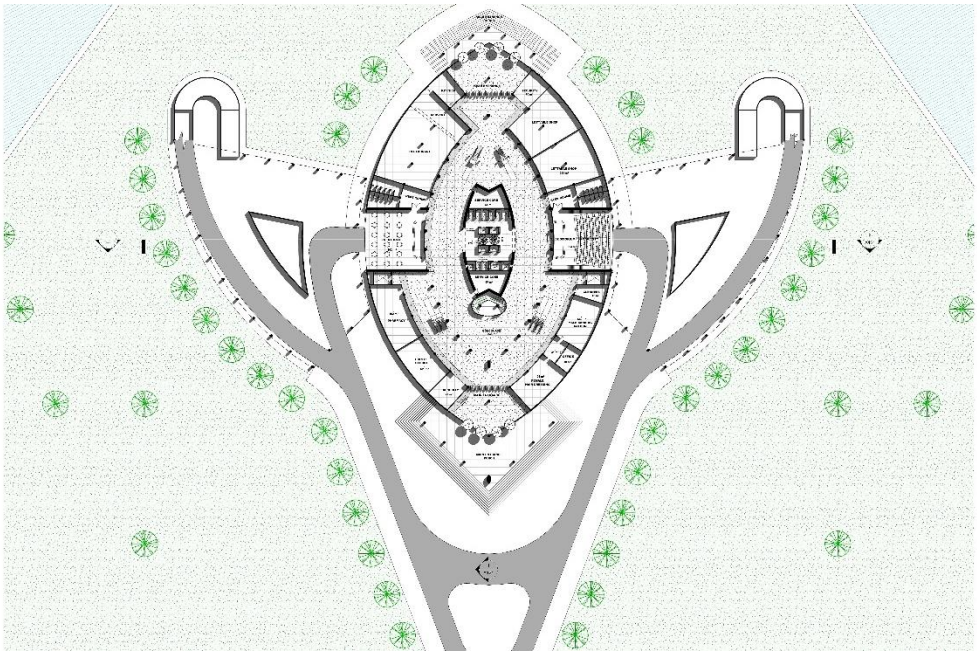
APPENDIX VII

Site plan for the proposed building



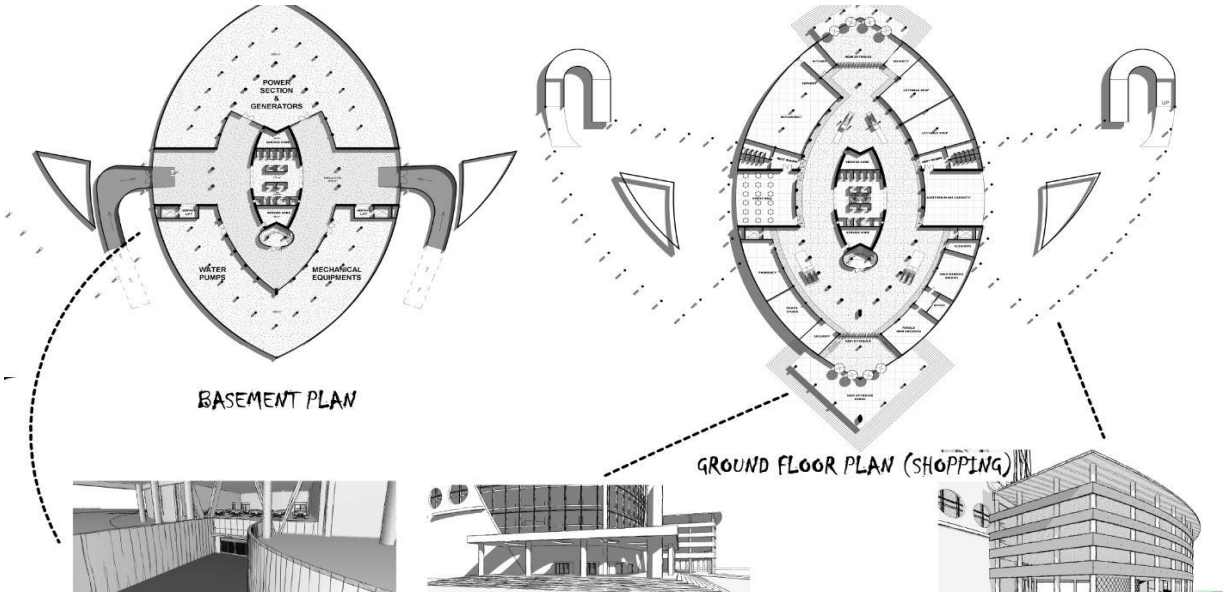
APPENDIX VIII

Plan on site



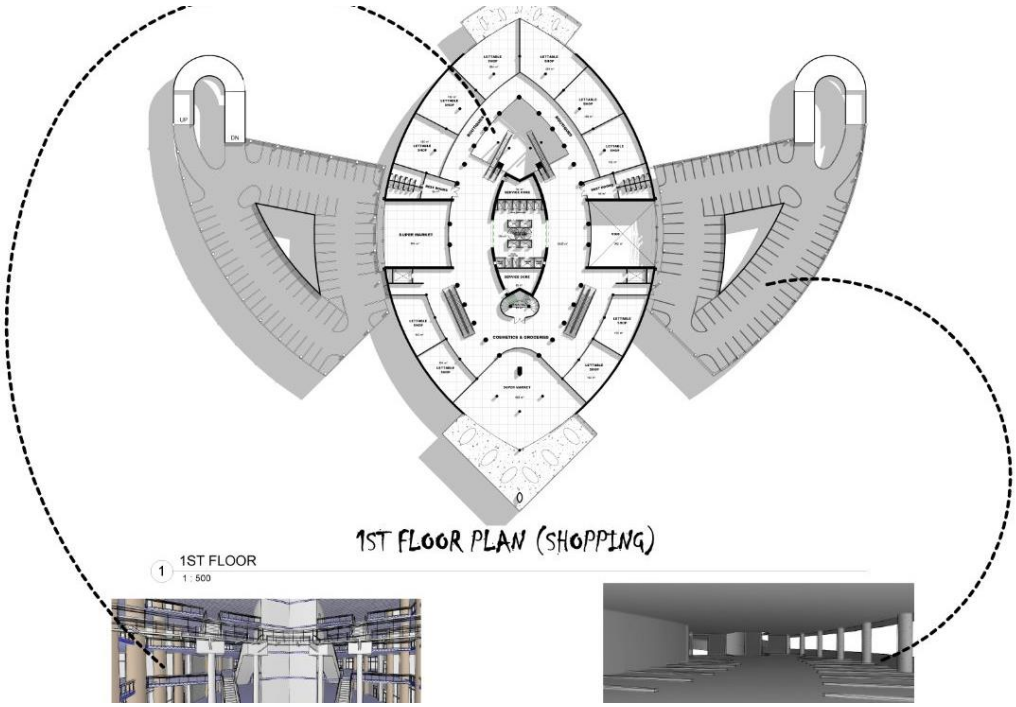
APPENDIX IX

Basement/ ground floor plan



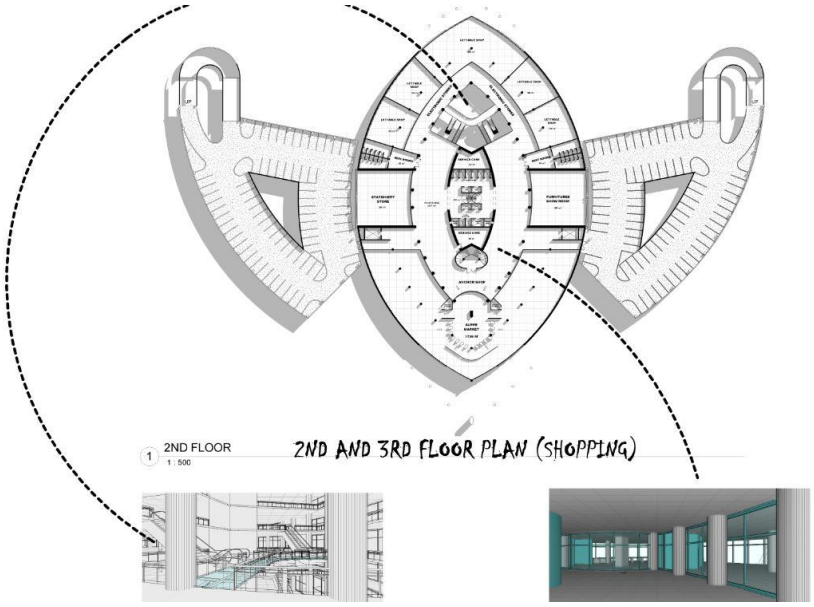
APPENDIX X

First floor plan



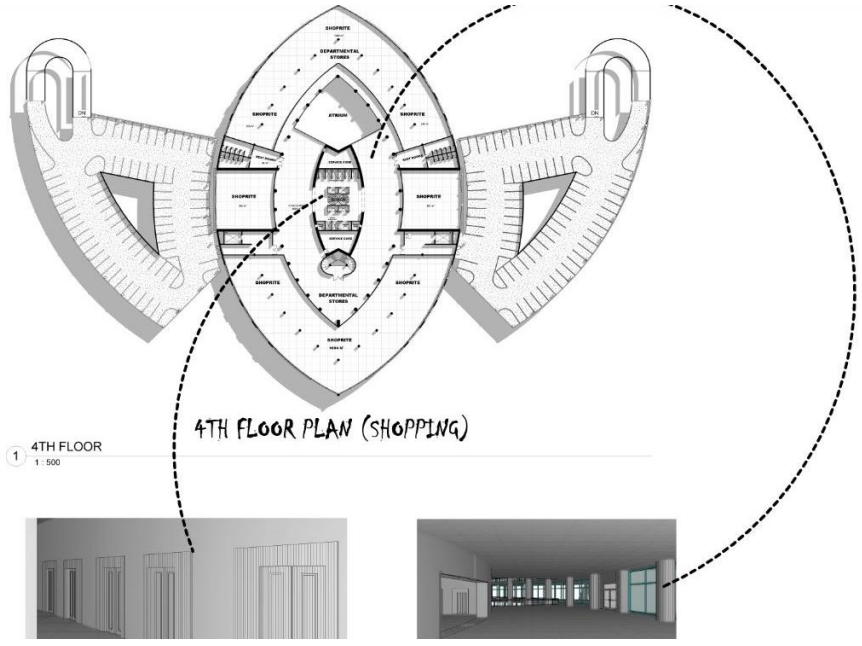
APPENDIX XI

Second/ third floor plan



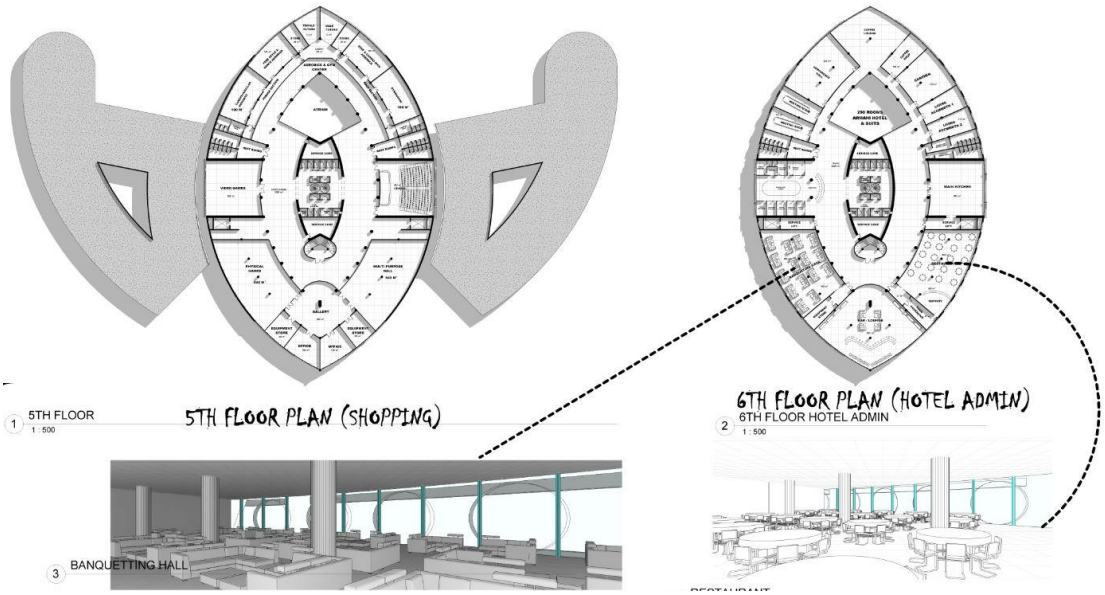
APPENDIX XII

Fourth floor plan



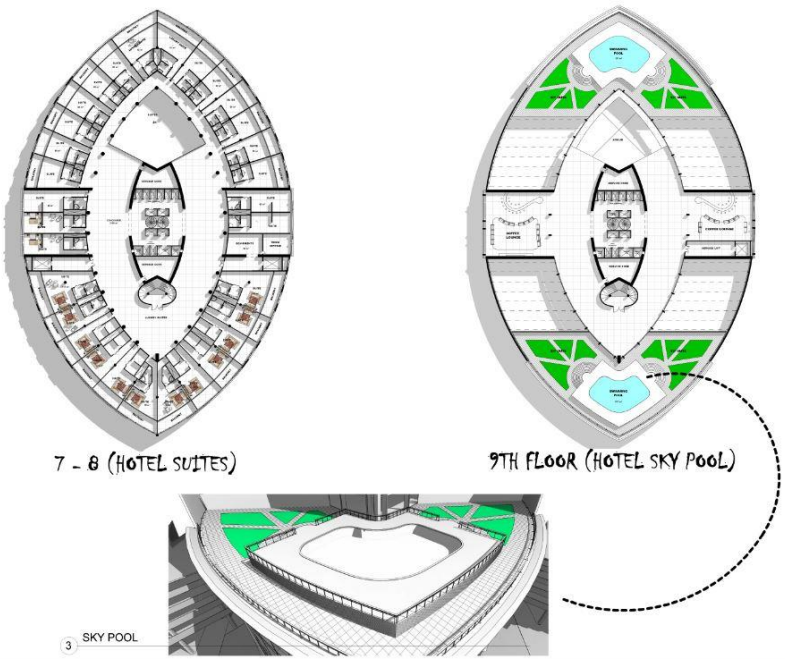
APPENDIX XIII

Fifth/ sixth floor plan



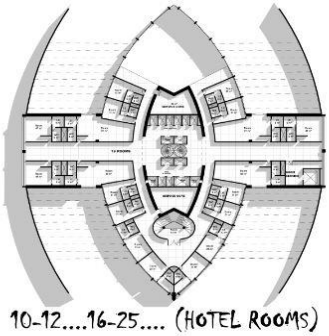
APPENDIX XIV

Seventh to ninth floor

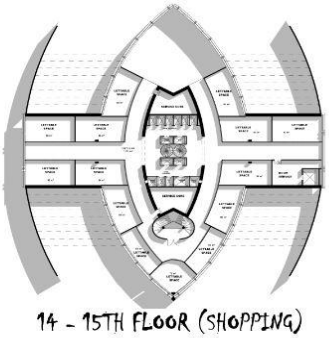


APPENDIX XV

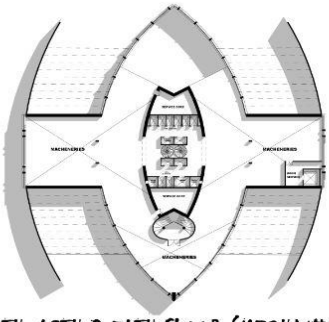
Tenth – twenty seventh floor plan/ mechanical floors



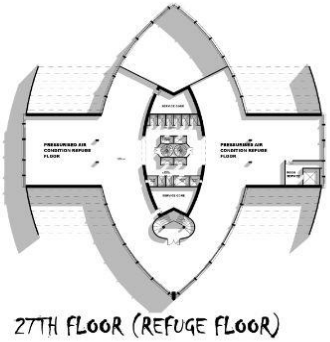
10-12....16-25.... (HOTEL ROOMS)



14 - 15TH FLOOR (SHOPPING)



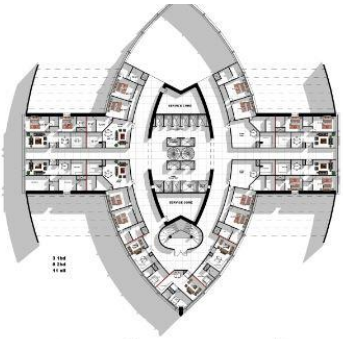
13 , 26TH, 42TH & 54TH FLOOR (MECHANICAL FLOOR)



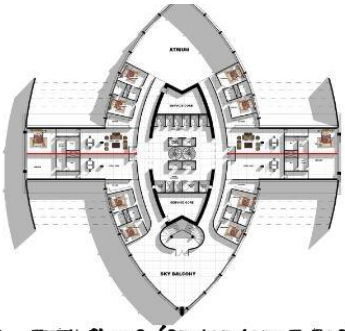
27TH FLOOR (REFUGE FLOOR)

APPENDIX XVI

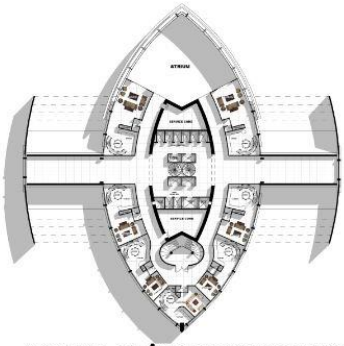
Twenty eighth – forty first floor



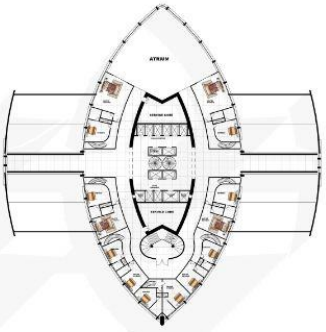
28 - 33RD FLOOR (RESIDENCES 1/2 BEDROOM)



34 - 37TH FLOOR (RESIDENCES 3 BDR)



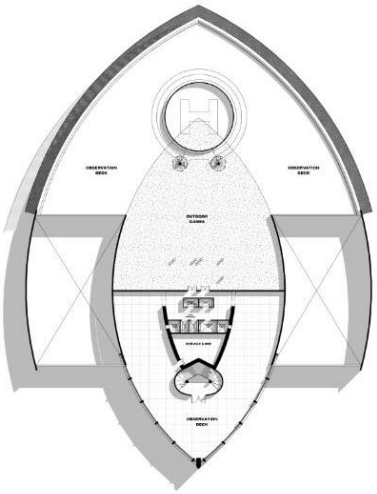
38 - 40TH FLOOR (RESIDENCES DUPLEX) A



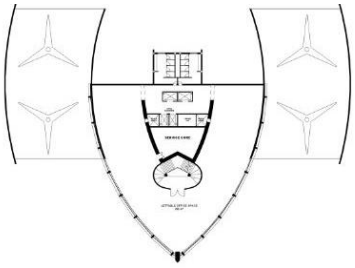
39 - 41TH FLOOR (RESIDENCES DUPLEX) B

APPENDIX XVII

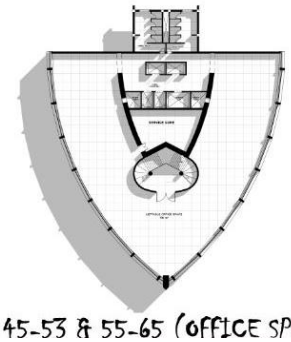
Forty third – sixty fifth floor



1 43RD FLOOR HELI PAD/ OBSERVATION DECK
1 : 400



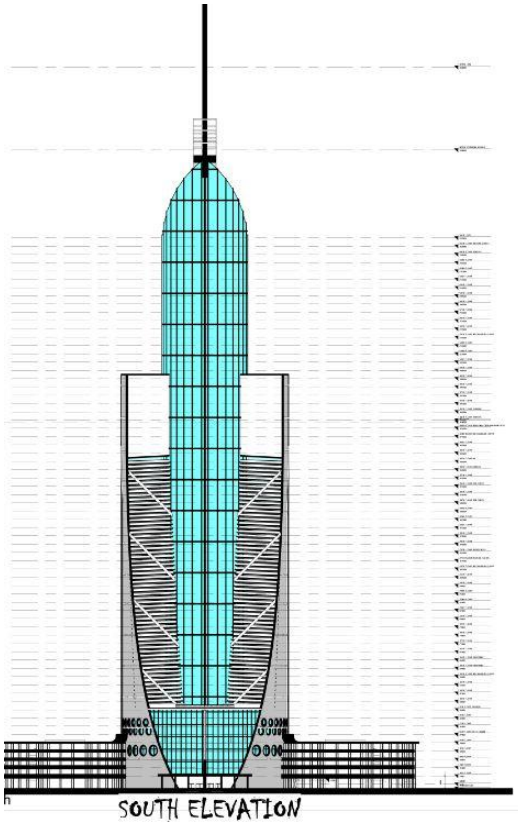
2 45TH FLOOR TURBINE
1 : 400

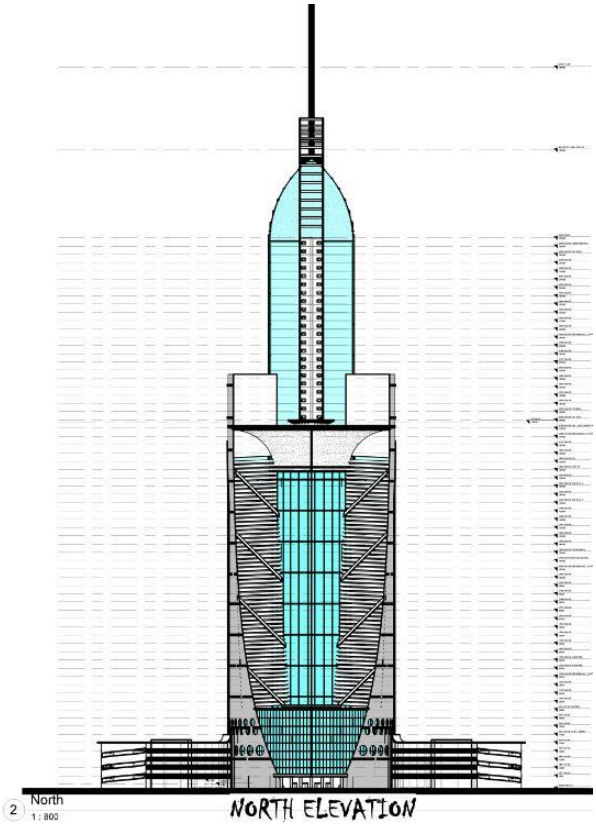


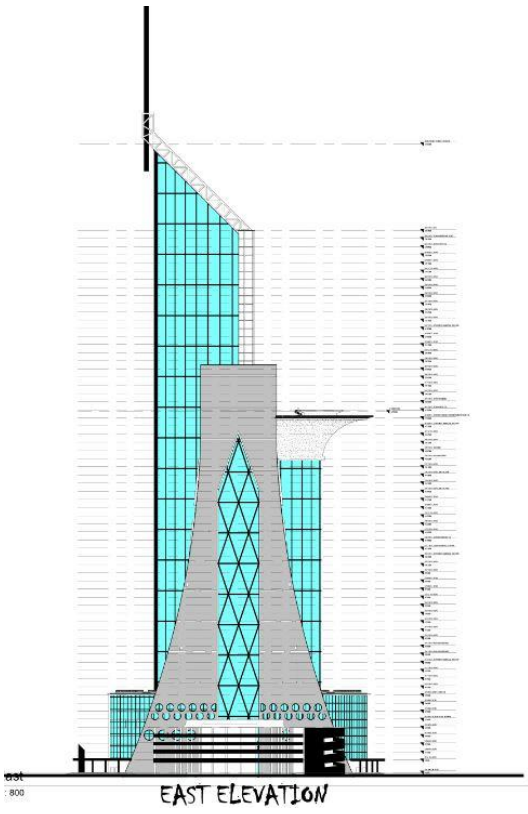
45-53 & 55-65 (OFFICE SPACE)

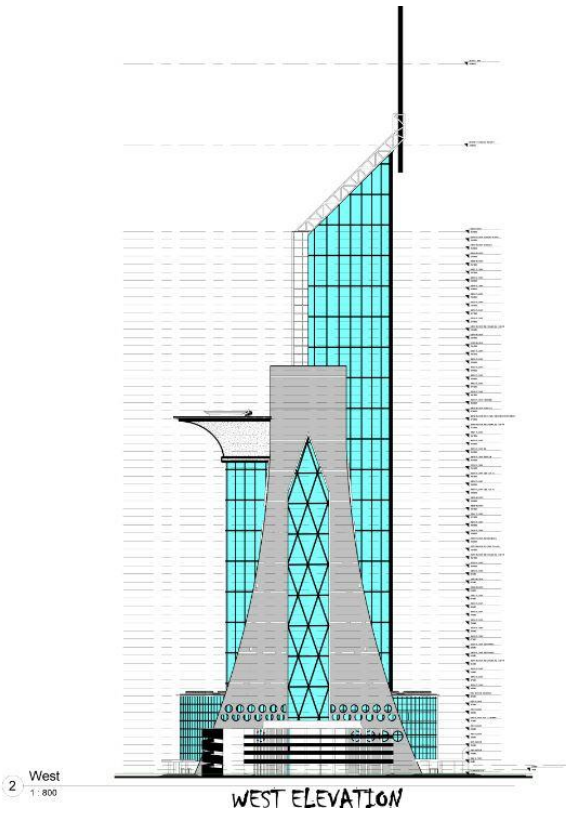
APPENDIX XVIII

Building Elevations









APPENDIX XIX

Building sections

