Wind Adaptive Building Envelope

For Reducing Wind Effect on High-rise

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1.Master thesis curriculum

1.1 Introduction

The nineteenth century was one of the most technically inventive centuries. Since then, it witnessed the application of new techniques and of new mechanical means in virtually every human activity. Also in architectural field, the new methods of construction were introduced which bring world architecture to reach another level with bigger buildings, faster construction, more sustainable buildings and also taller building. Before 1974 there were only a few high-rises that are taller than 300m, then Sears Building (Willis Tower) reached the height at 442 m in that year, Taipei 101 reached the highest point in the world at 509 m in 2004. After that, there are a number of designs being conducted to create a building in range of 500-1500 m (Irwin, 2009). The finished Burj Dubai stands as the highest building in the world in 2009 at 828 m height. It can be easily seen that there are tendency of high-rise construction to be higher which it is a part of human challenge nowadays.

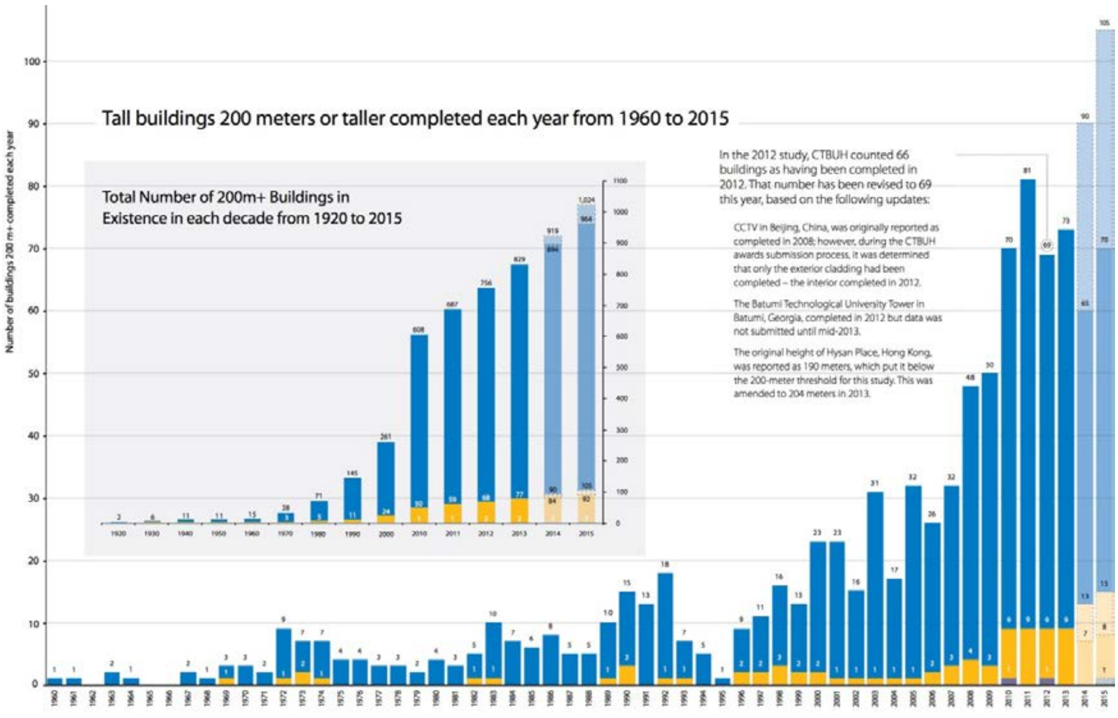

Fig 1.1: Growth in number of tall building from 1960-2015(the survey was made in 2013) (CTBUH, 2015)
Blue: Number of 200 m+ buildings
Yellow: Number of supertall buildings (300 m+)
Purple: Number of megatall buildings (600 m+)

"We practically designed the tower in wind tunnel"
The structural engineer for Burj Dubai: Bill Baker of Skidmore Owings Merrill

Higher the building stands, the wind loads will become more critical to the stability of the building structure. Preventing wind loads, there are many different systems were used. Three main methods are normally applied to the design which are stiffen the building, increase the building's mass and supplement the damping (Irwin, 2009). However, recently, adaptive system was introduced as the new method to offer the most effective solution in any problems that occur to a building, such as unwanted sunlight, lack of privacy, thermal bridge and wind loads.

In 2007, Braun Associates Architekten (architects) and Teuffel Engineering Consultant (structural engineering) proposed a 1080 m height tower – EVOLO Tower (Dr Patrick TEUFFEL, 2007). The tower is covered with its shape adaptive envelope that can be change its shape freely according to wind direction. The main idea is to deal and cope with power of nature but not against it. The aim for the design is to reduce drag force, cross wind movement and prevent organization of big wind vortexes. Since then, there were some studies in adaptive façade to reduce the effect of wind load. Some of them that are worthy mentioned are the studies that prove that not only shape but the roughness of the façade can possibly reduce drag force and under-pressure to the facade surface.

The aim for this project is to study and make research about wind behavior and its effect from research papers and self investigate. The final product will be a design of wind adaptive façade that reduce loads from the wind to building structure or normal façade element.

1.2 Problem statement

Nature of the wind in term of high-rise design is that in high altitude the wind has higher velocity than the wind in the lower level because of there is less friction to the earth surface or objects, such as trees or buildings. In an urban area, there are two different type of wind, first is high altitude wind which has constant velocity and direction, Most of the time, it is depended on the seasonal wind in the area. Second is the wind at low attitude which normally has lower velocity but because of the obstacles, the direction and flow of the wind can be manipulated and changed all the time.

Four sides of the building will receive different kinds of loads according to the wind direction, which are, front façade receives the wind positive pressure, and side façades handle vortexes and under-pressure force, while back façade has to resists pull force. Building shape and surface that are placed in the correct location will play a big role in reducing wind effect.

Most of the time, wind direction is unpredictable and the effect from the wind starts at the moment when the building get the impact, which the adaptive system needs to be able to adjust itself in a short period of time. The façade can finally be control by a complex command script which cooperates with detecting sensors, or it can be mechanism or smart material that can realize surrounding and change itself according to the influence of its environment.

1.3 Research objective

<u>Main objective:</u>

Design an innovative adaptive façade system for high-rise building that can adapt its shape or surface to reduce wind effect in any direction and any predicted velocity in order to reduce the needs in structure material to handle lateral load.

<u>Sub objective:</u>

Create an understanding in wind effect to a building with different shapes and surfaces.
Create possible options of how a building can deal with wind load by façade adaptive system.

1.4 Research questions

<u>Main question</u>

In what extend that adaptive shape and surface of the building can reduce wind loads in a high-rise building with highest efficiency in construction cost, material saving and up-keep cost?

<u>Sub question</u>

What are the effects of the wind to a building and how shape and surface of a building alter those effects?

By dividing building in four sides according to wind direction, what kind of loads and effect that occurred in those sides?

What is the most suitable envelope shape or surface that is best to deal with different wind effect in each side of the building?

What are the criteria or values that indicate the load from the wind to a building?

How to define if small façade components or big façade system is more suitable in term of maintenance, construction and safety?

What type of control and wind detecting system that is has fast reaction, less maintenance, easy to control and suitable for wind adaptive façade?

What is the material that performs the best as wind protection and still be able to seen through?

How is this additional building envelop connect to building main structure?

1.5 Scope of study

Building definition:	250-400 m height		
	50x50 m^2 floor plate		
	Multi-function used		
	Width and length ratio = 1 (square or circular) for floor plate shape		
Location:	Urban area, Equatorial zone		
	No seismic load (earthquake)		
Wind speed:	Typhoon wind speed	118-156km/h	(32.78-43.33m/s)
	Severe tropical storm	89-117	km/h (24.72-32.50 m/s)
	Tropical storm	62-88	km/h (17.22-24.44 m/s)
	Tropical depression	<61	km/h (16.94 m/s)
Wind behavior:	Undistributed		
	Can be in different velocity or density in different height		
	Unpredictable direction		
	Vortex shedding is possible		
	Higher velocity in higher altitude		

1.6 Methodology & Time planning

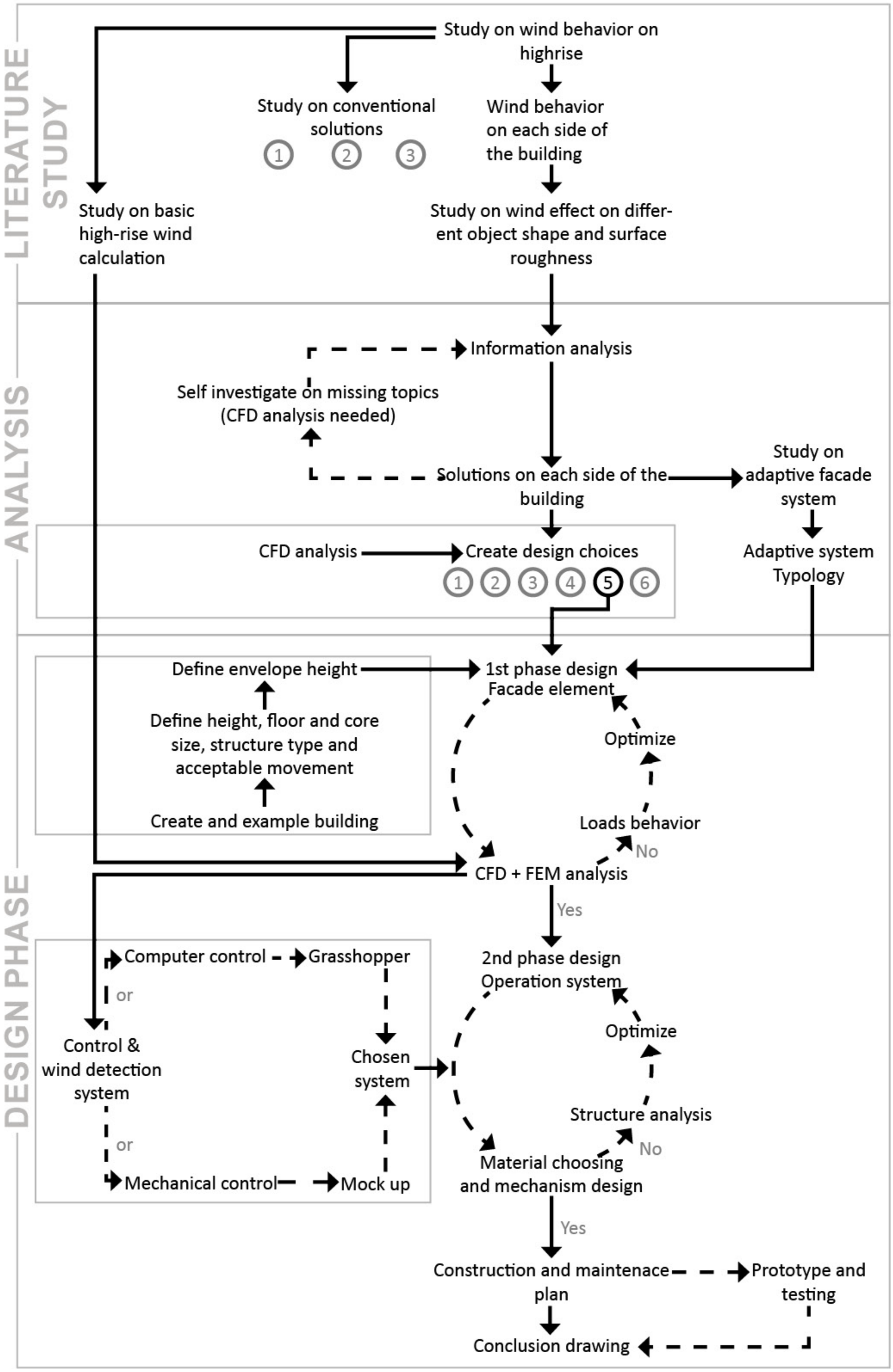

Fig 1.2: Project methodology

Presentation	P1								P2								P3							P4							P5
Course Week	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10	4.11
Literature Study																															
Wind Behaviors																															
Wind Effects																															
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Selecting Material																															
Drawing																															
Prototype																															
Conclusion																															
Comparison																															
Feasibility																															
Further Research																															

Table 1.1: Project time planning

2.Wind

2.1 Basic wind behavior

As we all know, wind is the natural phenomenon which occurred by flowing of air. Two basic things about air that need to be considered are that it has mass and viscosity. Mass in the air means that to move the air we need energy to create a movement, in contrast, stopping the movement of the air it will also release some energy as well. Viscosity creates friction between two air flow direction and between air and the object. Viscosity can also be the cause of a flow of the air to influence still air to move along with it. Obstacles such as building that stand in the part of the wind; they convert the wind's kinetic energy into pressure to their surface and become *wind load*.

2.1.1 Wind speed

Wind speed, which influences the pressure to a building surface, has higher velocity by the increasing of the height. Basic explanation is that closer to the earth surface, there are many obstacles such as terrain, buildings or trees, which create friction and slow down the wind speed. According to Euro standard (Eurocode, 1995), there are 5 terrain categories which are coastal are or open sea, flat area with only negligible vegetation, area with low vegetation and isolate obstacles, area with regular cover of vegetation or buildings such as village or suburban terrain or forest, and area which at least 15% of the surface covered with building with average height more than 15 m. The terrain category defines roughness length of the area which is needed in wind calculation.

	Terrain category	Roughness Length, Zo (m)
0	Sea or coastal area exposed to the open sea	0.003
1	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0.01
2	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0.05
3	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0.3
4	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1

Table 2.1: Terrain category (Eurocode, 1995)

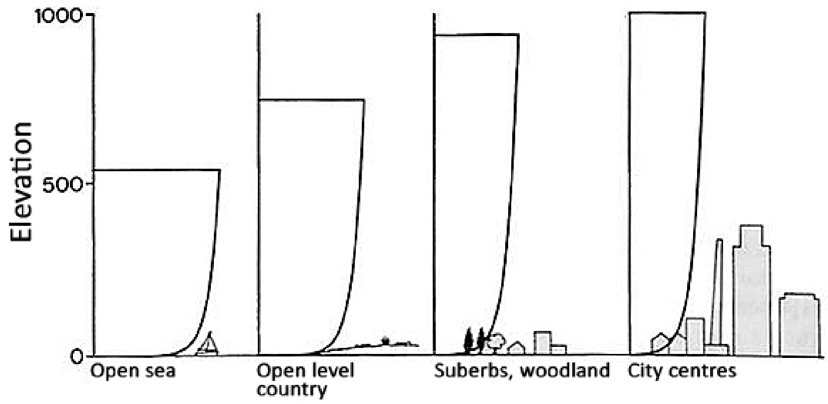


Fig 2.1: Mean wind profile for different terrains (P. Mendis, 2007)

According to Taranath's book (Taranath, 2012), over the height of 366 m above ground, surface friction has no effect to the speed of the wind. The movement of the wind speed in this level depends only on seasonal and local wind. The height at this level is called the *atmospheric boundary layer.* It is seem to be that at the higher altitude the wind is more likely to have less turbulent character. It has less fluctuation in its velocity and direction compare to wind that is close to earth surface which is affected by obstacles and being influenced to form eddies, vortexes and change in direction.

It can be concluded that wind in the higher altitude has higher velocity which create higher pressure to the building but it has less chaotic behavior, while wind at low altitude create less load to the building but it is more difficult to predict the direction, speed and type of flow when it approach the building. From Teuffel's research (Dr Patrick TEUFFEL, 2007), he gave the possible assumption that variation of wind direction to the height would take a height of 300 m and an estimate change of 10 degrees. However, a sudden change in wind direction is also possible and happen within a very short period of time, this is commonly observed with the passing of a warm front.

2.1.2 Along and cross-wind load

Effect from the wind load to an object or to a building is a complex phenomenon by its flow effect, flow separation, the formation of vortices and development of the wake. These wind fluctuation create different pressure on the building's surfaces and transfer to the structure of the building. Under the collective of these fluctuation forces, causes the building to vibrate in rectilinear and torsional modes.

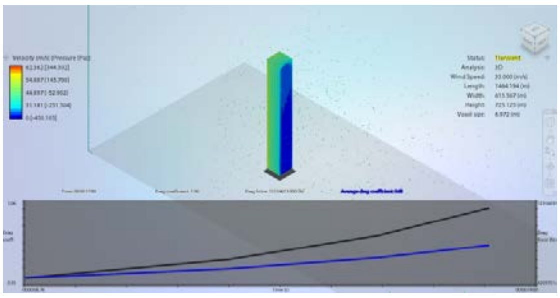
<u>Test on development of wind load to a building</u>

A simple test was conducted to change in location of the wind pressure to the surface. The example object was imported in to computational fluid dynamics (CFD) software to make a quick analysis which can be present in a simple graphic. The object is 50x50m width with 400m height is placed in a simulation wind tunnel with wind speed of 33m/s in the perpendicular direction to the object wall.

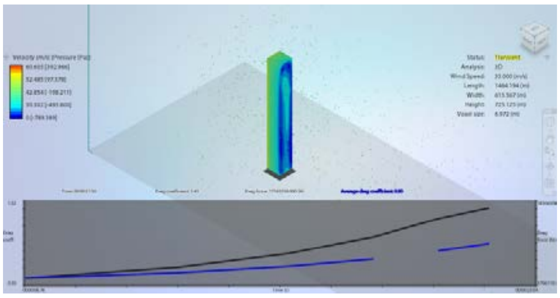
The result show that the location of pressure that is occurred by the wind started in two positions, the front wall where the wind approaches and the back wall at the opposite side. The pressure in the front wall was in positive value and increases its value in the early part of the test and then remains steady afterward. The pressure at the back was in negative number which pulls the object along wind direction. However, the location of the negative pressure moved to the side of the object and increases its value.

These effects can be explained that at the moment when the wind approached the object, it created a separation area behind the object that cause drag force from negative pressure to the back wall. However, once the separation area become bigger, there was some turbulence in the area. During that time, the velocity at the leading edge of the side wall became faster. From Bernouli's Principle, the increasing of velocity in fluid flow will simultaneously decrease the fluid pressure. According to the increasing in wind speed, high negative pressure on the side wall was occurred.

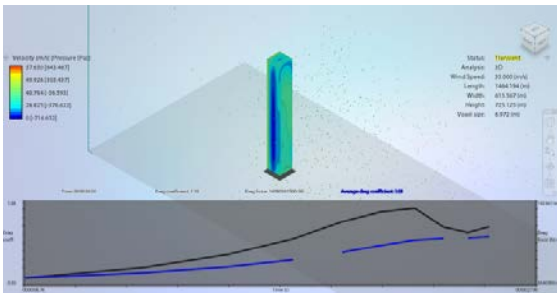
The test shows that the back wall negative pressure happens only for a gust, but a long continuous wind creates under-pressure at side wall and causes cross-wind direction loads. The alone-wind load from the analysis is occurred to the object at the beginning of the attack and then reduce it value and is turned in to side wall pressure that cause the cross-wind load. In a long continuous wind the small pressure and vibration at the side of the building can cause a failure in structure, especially in the case that the vibration of the side pressure appear to has the same frequency as the vibration of the building. It can increase the moving length into a critical position that the structure can handle.



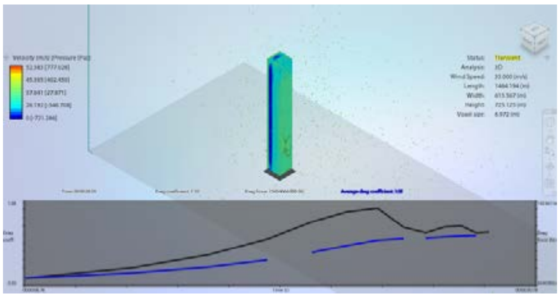
17 second after impact: negative pressure stay at the back of the object.



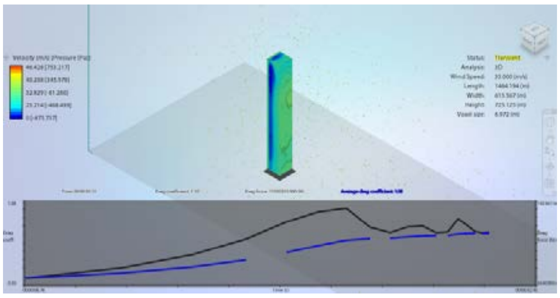
21 second after impact: the negative pressure moved to the edge of the back wall



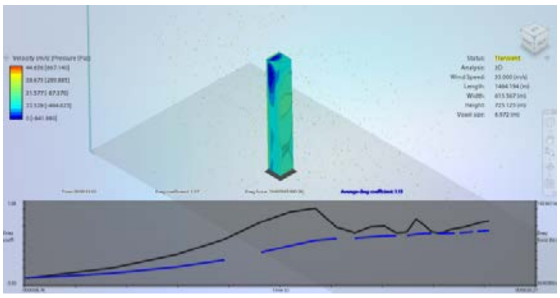
26 second after impact: the negative pressure moved toward the leading edge of the side walls



28 second after impact: the negative pressure locate itself at the leading edge



30 second after impact: the negative pressure start to move upward



32 second after impact: the negative pressure locate itself at top part of the leading edge

Fig 2.2: Result on location of negative pressure on test object according to wind from the top-left side (Autodesk Flow Design)

Vortex shedding

In a low wind speed (22.3-26.8 m/s), the building spreads the air flow into two side of the building which is the cause of under-pressure at the leading edge of the side façade. When the vortices are shed symmetrically, it breaks away from the building surface and it creates pull which an impulse is applied in the transverse direction. However, with low velocity, shedding occurs in both side of the building equally which create no vibration to the structure, only along-wind oscillations is experienced by the building.

At higher speed, can happen alternately different in both side of the building (fig 2.3). In this situation, there is a combination of along-wind and cross-wind motions. Moreover, if the transverse impulses that occur both side of the building create a frequency that is precisely half of the along-wind impulse; it will give rise to vibration in cross-wind direction. This phenomenon is call *vortex shedding* or *Karman vortex* (Taranath, 2012).

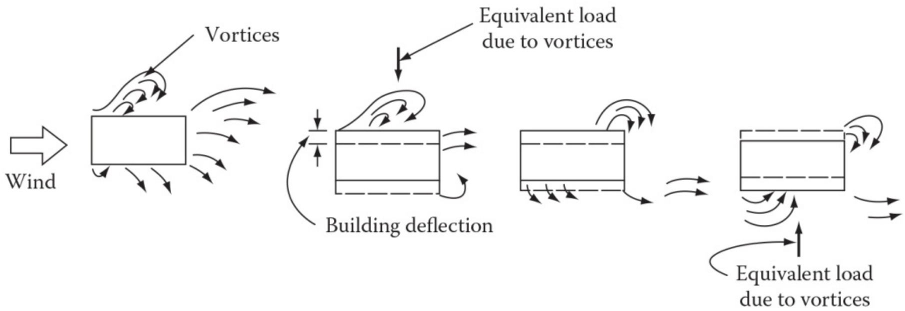


Fig: 2.3 Vortex shedding: Periodic shedding of vertices generates building vibrations transverse to the direction of the wind (Taranath, 2012)

Reducing vortex shedding

There are several solutions to reduce vortex shedding according to Irwin paper (Irwin, 2009) which relate to how to select building shape.

- Softened corners: the softening should extend about 10% of the building width in from the corner. For example, Taipei 101, the corners were stepped in which result in 25% reduction in base moment.
- Tapering and setback: The building that has varies width along the height confuses the vortices to shed in different frequencies in different height and they become in coherent and reduce the association fluctuating force.
- Varying cross-section shape: the similar effect can be achieving by varying the cross-section shape with height.
- Spoilers: It can be added to outer surface of the building. The spiral Scruton strakes always be used on circular chimneystacks. Also, vertical fins that run along the building height can be acceptable too.
- Porosity or opening: Opening through the building which allows the air to flow from front façade and leave at the back weaken and disrupt the vortices (fig 2.6: left image).

2.2 Influenced by objects to wind effect

There are mainly 3 loads that are occurred to an object according to wind

1. Front wall pressure load: it is caused by direct pressure from the approaching of the wind. Also there is a high density air that cannot move because it is blocked by the flow line shape itself as a dome in front of the wall
2. Side wall suction: it is cause by the shedding of the flow from front wall to side wall. In high wind velocity, it can be the cause of vortex shedding
3. Back wall pull force: when the wind flow pass the object, the flow at one side cannot reach the flow at the other side at once. The movement of two flow line and viscosity of the air influences the still air at the back of the object to move along and cause suction at the back wall

However, the characteristic of the can be designed. It can be done by two main options, designed by shape of the object or designed by typology of object surface.

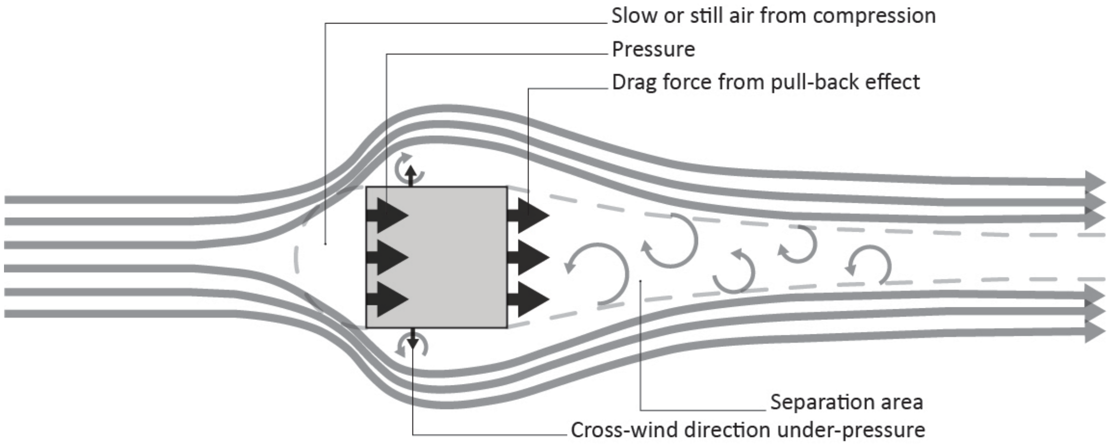


Fig 2.4: Wind characteristic to an object

2.2.1 Object shape

Aerodynamic behavior always is in an important consideration of designing airplanes, cars, ships or even a tall building. Aerodynamic design has the main idea to get rid of problem from vibration and also reduce drag force of an object.

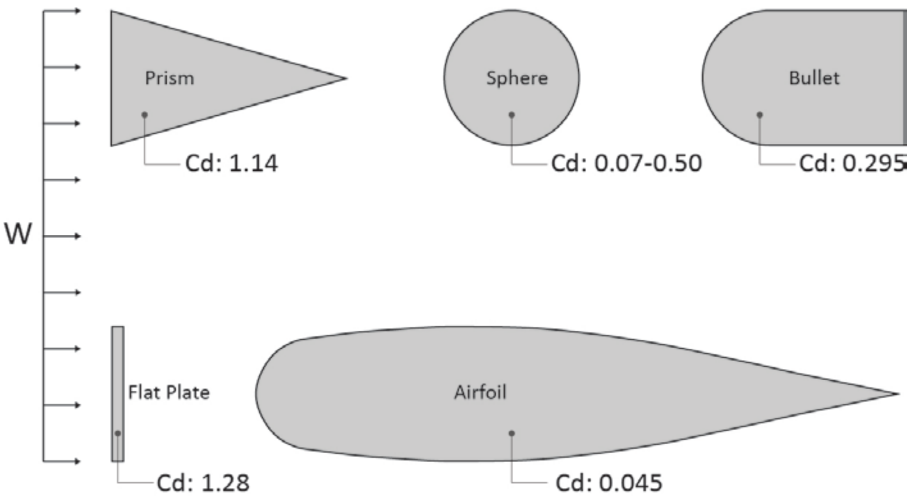


Fig 2.5: Shape effects on drag (2015)

From fig 2.5 shows the different in drag coefficient values in the objects in different shape which were tested in a wind tunnel. Although the frontal areas of these objects are in the same size, the drag coefficient that is affect by the shape is varies. Streamlined symmetric airfoil gives lowest drag because at the tail of the shape allows the air to flow along the surface and leave only small separation area at the back. Compare to a flat plate that has the highest drag coefficient because it has flat front surface and the shape creates big separation area at the back which pull back the object.

The length of the building also perform different result in reduce drag force. In fig 2.6, the drag forces are presented in pressure coefficient which the increasing of building length along the wind can reduce negative pressure at the back façade

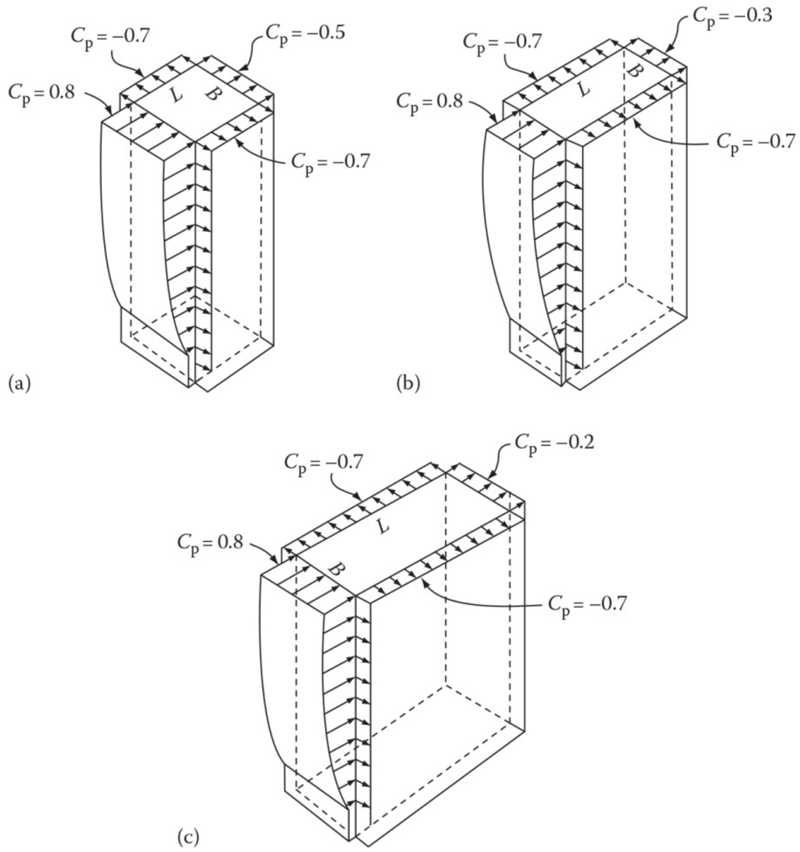


Fig 2.6: External pressure coefficient (Cp)with wind direction from right side of each image.

Plan aspect ratio L/B: (a) 0 < L/B < 1

(b) L/B = 2

(c) L/B > 4

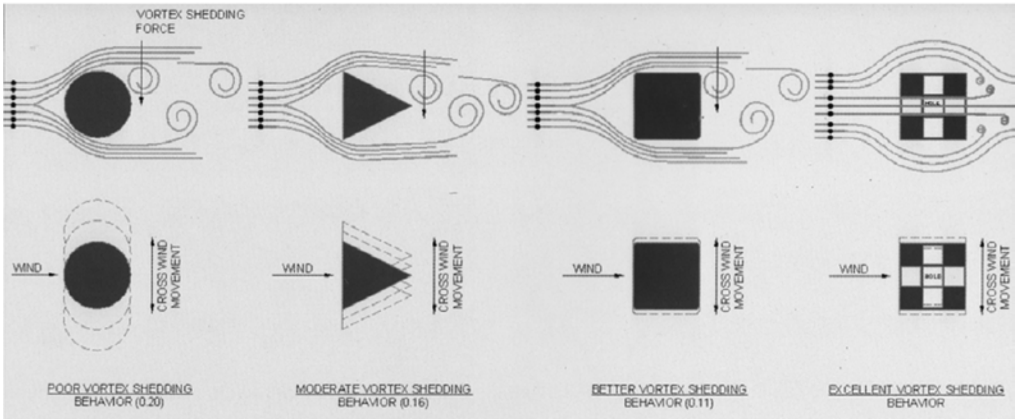


Fig 2.7: Vortex shedding behavior according to building shape (Dr Patrick TEUFFEL, 2007)

Fig 2.7 shows the effect from vortex shedding in different building shape. As mention before, vortex shedding causes vibration to the structure in cross-wind direction. Circular shape building shows the biggest movement according to the vortices. However, this project is located in a very wide possible areas, the direction of the wind is presumed to be unpredictable which in this case circular shape building might perform the most suitable result.

2.2.2 Object surface

Aerodynamic and hydrodynamic property of an object depend mostly on its shape, however, there are several research and existing objects show that surface smoothness and pattern can be used to create specific flow effect that can improve the property. As generally expectation that smooth surface is better in minimize friction from the flow to the surface, which is not completely true in many situation. For example, golf ball dimples was designed to reduce the separation area and create lift while it is spinning.

<u>Case study</u>

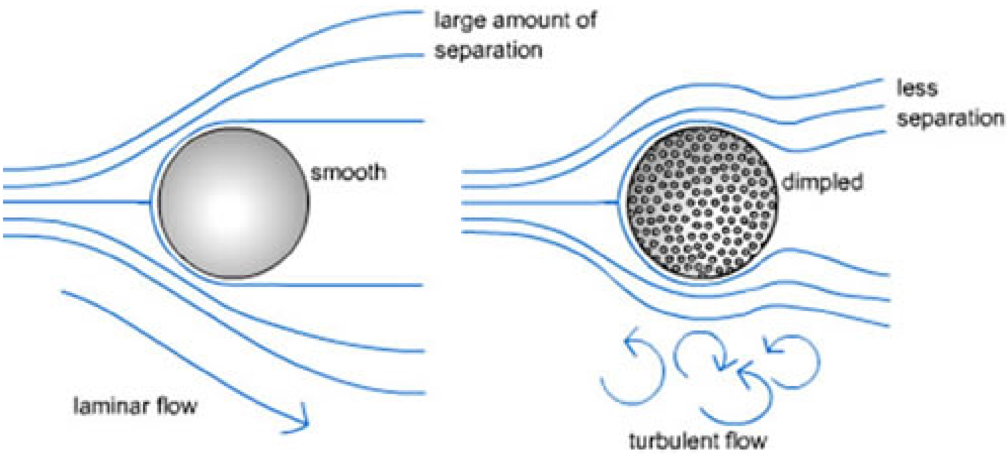


Fig 2.8: Different aerodynamic properties between a ball with smooth surface and surface with dimples (golf ball). Rough surface creates small turbulence close to the surface and draw the flow closer to the back surface of the ball which reduce the separation area and drag coefficient. (image from (Lorenzo Lignarolo, 2011))

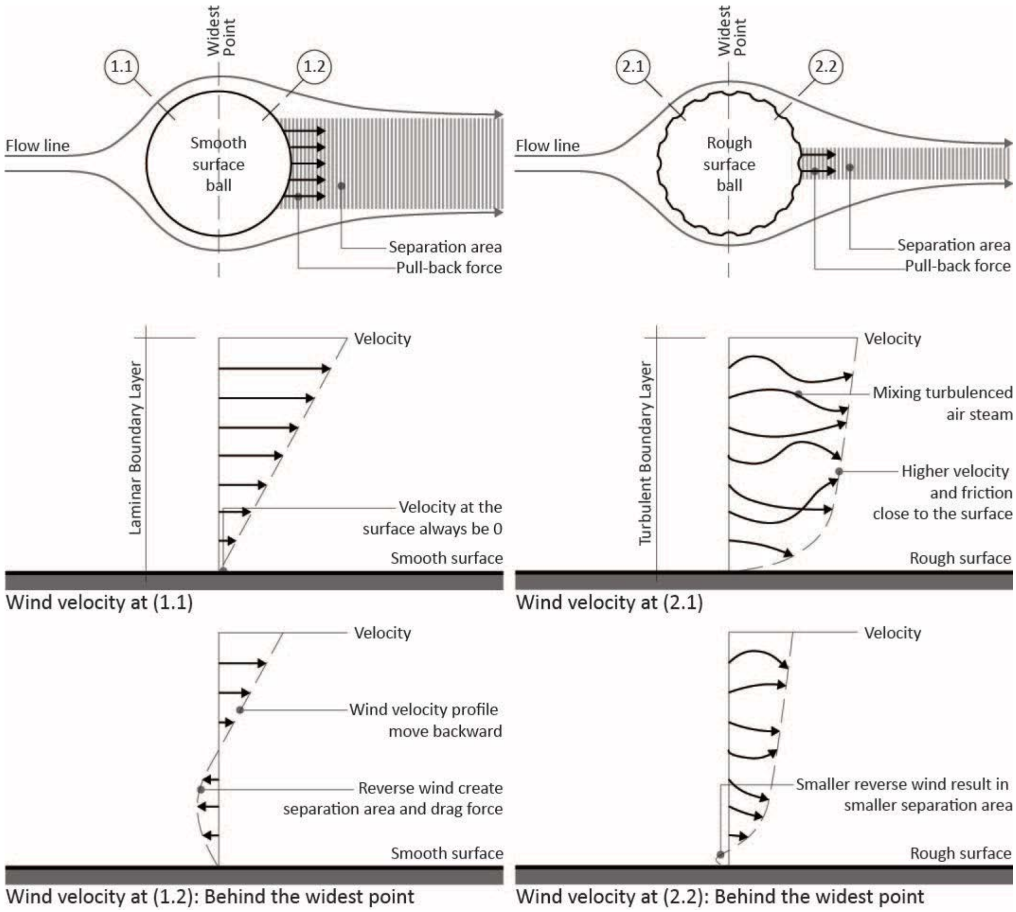


Fig 2.9: Surface air velocity on smooth and rough surface balls which analyze how rough surface can reduce drag force (redraw from(Velo, 2015))

Another example is shark's dermal denticles (skin) are ribbed with longitudinal grooves which improve the efficiency of water flow on their surface. Compare to smooth surface, the groove prevent turbulent vortices or eddies in fast water, and keep the flowing that close to the surface in the comparable speed to the flowing further away from the shark. The reduction of eddy formation is done by the groove are below (Yann, 2015)

1. The grooves reinforce the direction of the flow by channeling it.
2. They speed up the slower water at shark's surface, as the same volume of water going through a narrower channel increases in speed.
3. Conversely, they pull faster water towards the shark's surface so that it mixes with the slower water and reduce the speed differential
4. They divide up the sheet of water flowing over the shark's surface so that any turbulence created result in smaller, rather than larger vortices.

From golf ball surface and shark's skin, there are several design that are developed from the ideas, such as "Fastskin" FSII swimming suit that is developed by Speedo by mimic shark skin to a full body swimming wear. The swimming suit was designed by using computer software to simulate the movement of the swimmer and place the streamline groove in the micro scale to improve the movement in different zone of the body (such as arms and body ((Barry Bergdoll, 2007)). Anther “Fastskinz” is the vinyl membrane that is designed to be place on vehicle surfaces like stickers. The special design for the membrane is that it contains small dimples (similar to golf ball) which they generate turbulence when air passes over them. They reduce they reduce the air pressure and enable an object to more easily slip through the air. Fastskinz generates a layer of turbulent air that reduces drag coefficient and gas using by 18-25%(Gladwell, 2015).

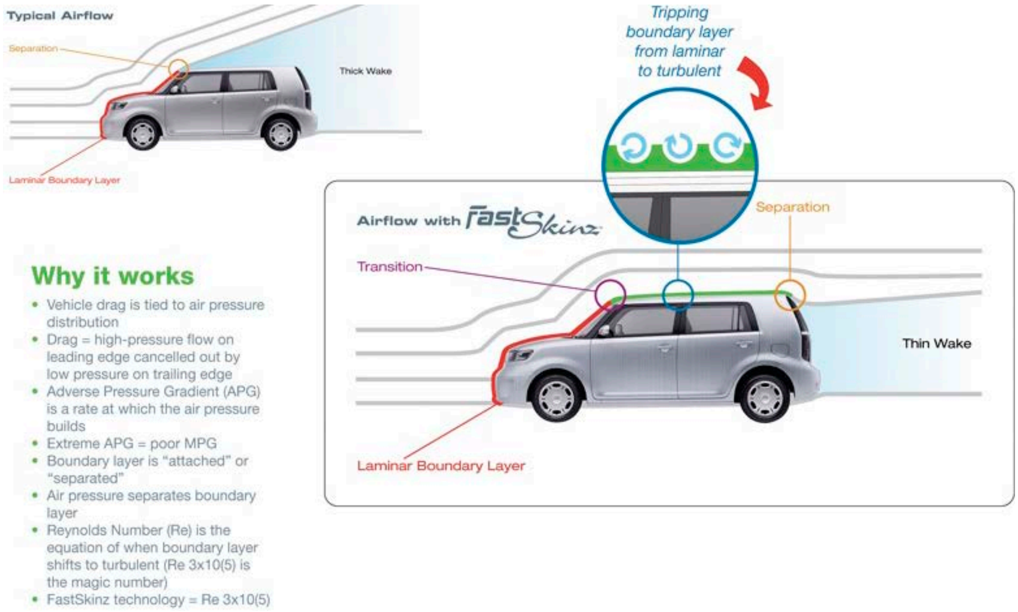


Fig 2.10: Fastskinz wrap for reduce drag coefficient of vehicle and gas usage


Fig 2.11: Fastskinz under wind tunnel test (FastSkinz, 2015)

<u>Test on effect of wind load on different surface</u>

Three computer models were set in CFD software to test the different in values of drag coefficient. All of them represent circular shape high-rise building with diameter of 50m but they are all different in surface roughnesses which are smooth surface, rough surface, and hybrid surface. The rough surface was designed to be vertical stripes along the height of the building. The situation in wind tunnel was set to be the same in all models which has wind speed at 33 m/s. The tests were performed only in 2D analysis.

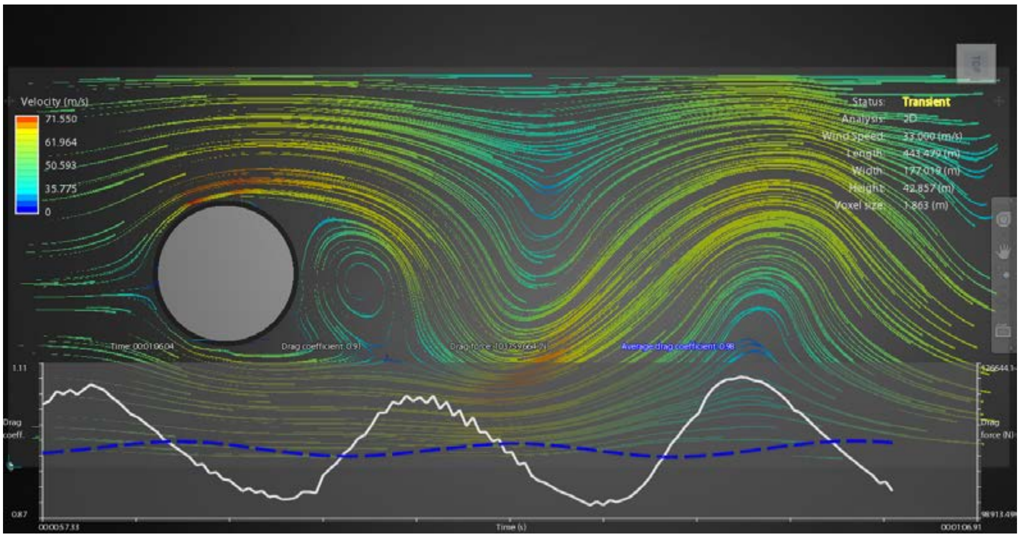


Fig 2.12: Wind analysis for *smooth surface* circular shape building. Drag coefficient is 0.91 (average is 0.98), highest wind velocity is 71.55 m/s and range of pressure is from -2548.53 to 1679.85 pa.

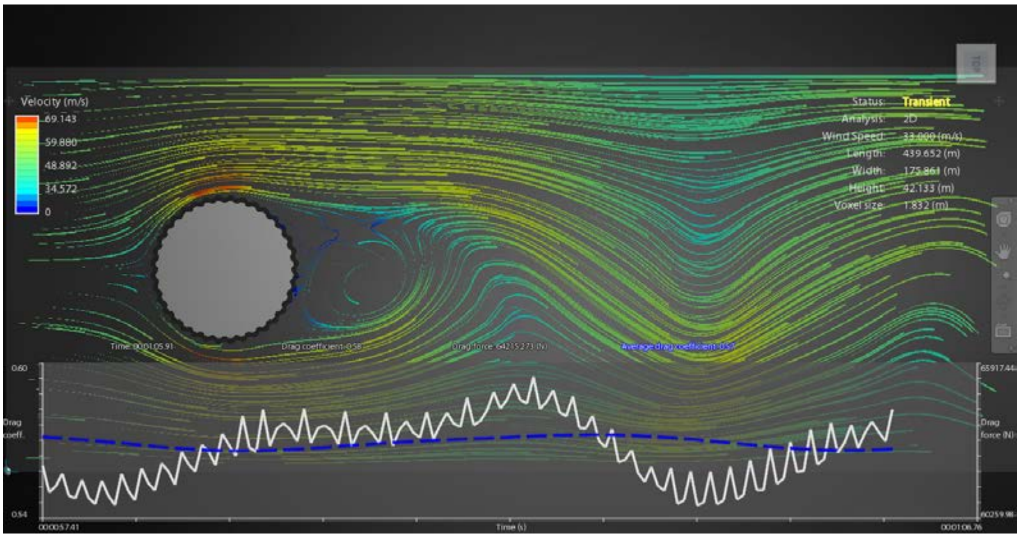


Fig 2.13: Wind analysis for rough surface circular shape building. Drag coefficient is 0.58 (average is 0.57), highest wind velocity is 69.14 m/s and range of pressure is from -2255.56 to 1285.81 pa.

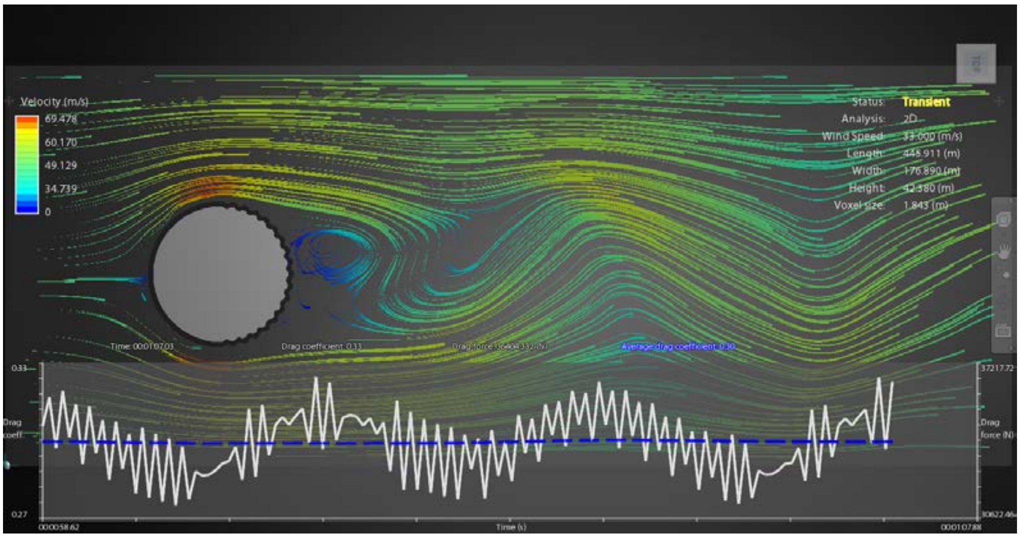


Fig 2.14: Wind analysis for *hybrid surface* circular shape building. Drag coefficient is 0.33 (average is 0.30), highest wind velocity is 69.48 m/s and range of pressure is from -2425.24 to 1166.41 pa.

By comparing the results, it can be clearly seen that the values of drag coefficient are highly different in each model. Drag coefficient in the rough surface model reduce approximately 42% from the smooth surface one, the hybrid surface drag coefficient 48%, and comparison between hybrid surface and smooth surface 69.5% of drag coefficient is reduced.

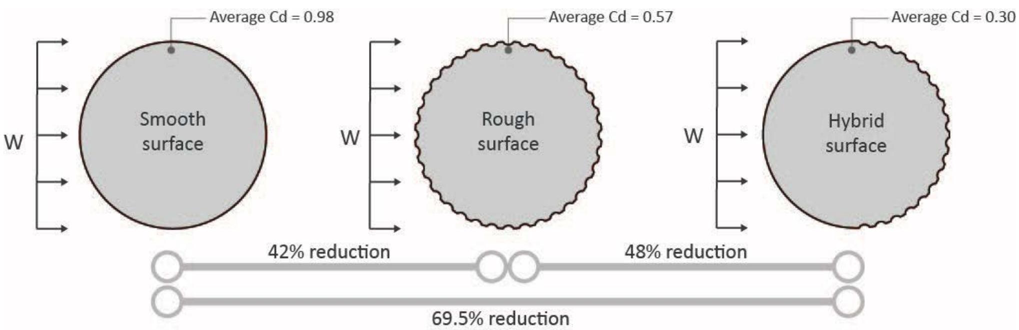


Fig 2.15: Different in drag coefficient in different building surface

The result from smooth and rough surface model can be predicted in the beginning with the separation area reduction of golf ball. However, the hybrid surface model that has front smooth surface and vertical stripes roughness surface at the back can reduce drag coefficient to almost 70% compare to the smooth one is an outstanding result. The prediction of how this phenomenon occurred is that, with smooth front façade, it reduces friction to the surface which results in reducing front façade positive pressure. The laminar flow from front façade after pass the widest point of geometry might be easier to be pulled in close to the rough surface and results in smaller separation area.

<u>Surface Roughness</u>

There are several researches that are conducted on different surface roughness (roughness size) to wind load. The interesting one was done by (E. Maruta, 1998), which the test was done in physical wind tunnel on 5 building models. These physical models are different in roughness size and façade pattern. One is the model that was covered by sand paper which has smallest roughness size (0.21 m in full scale), three more are models of building with balconies with different width (0.63, 1.25 and 2.50 m in full scale), and the last one is with balconies with mullion (0.63 m in full scale).

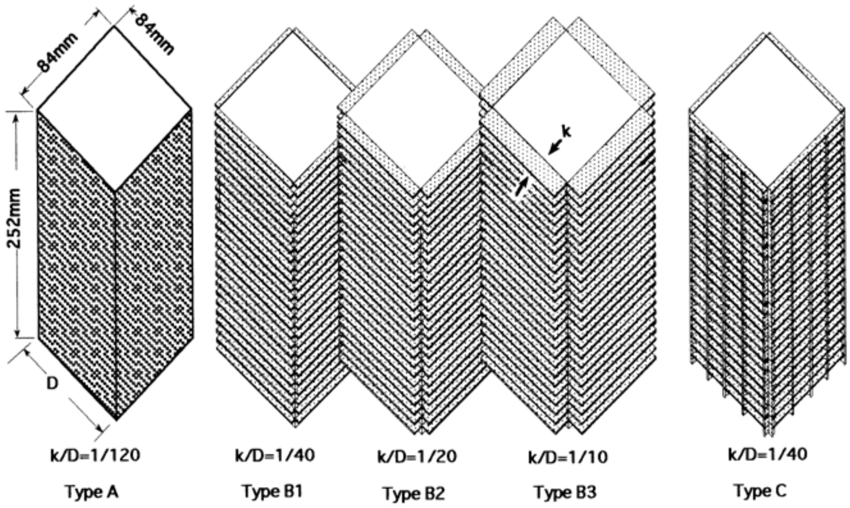


Fig 2.16: Configuration of models and surface roughness (E. Maruta, 1998). k/D is roughness size (balconies width/dept of the building).

The result shows that changing of roughness size has only small effect on front wall (windward face), however, suction forces at the side walls are remarkably reduce by the increasing of roughness size. Compare to roughness length at 0m, the 1.25m (type B2) reduce the under-pressure close to the building upwind edge about 25-30%. Which the result has been concluded that increasing the roughness size can reduce separation bubbles which cause the under-pressure at the leading edge of the side wall.

Another research was conducted by (Lorenzo Lignarolo, 2011)on building surface roughness but vertical pattern. The test was done in CFD software only for at the side façade of the three square building buildings, which have different type of façade, smooth surface, horizontal pattern roughness (balconies) and vertical pattern roughness (fins). The result was presented in values of wind velocity at 0.5m away from the surface, which it is possible to notice how much the flow field is affected by the present of the roughness element.

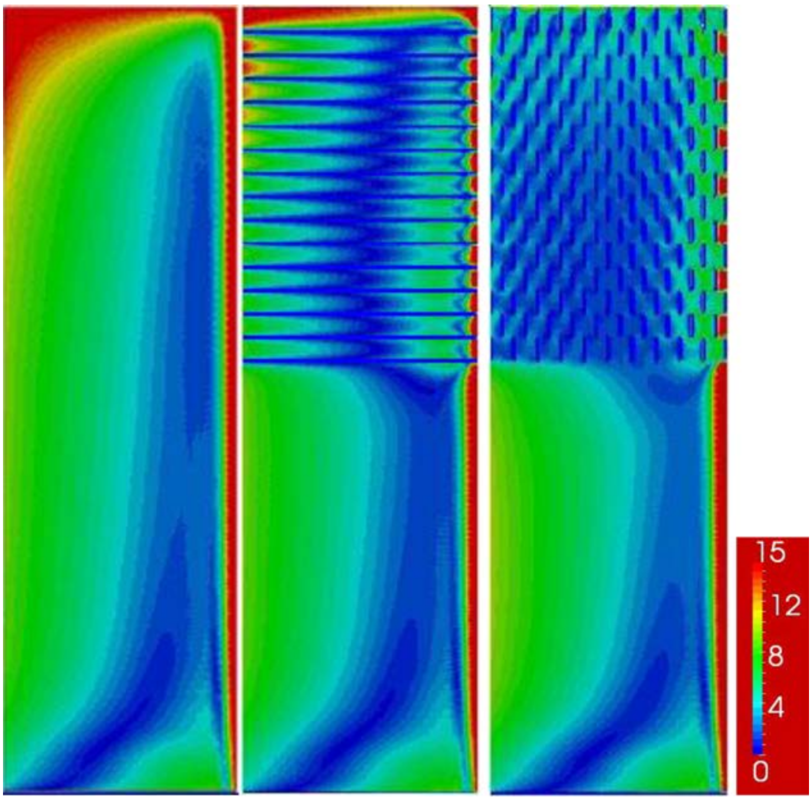


Fig 2.17: Velocity field on the side wall of the high-rise building (case A2, B2 and C2). The wind is coming from the right-hand side. (Lorenzo Lignarolo, 2011)

The result shows that roughness element in vertical direction (case C) provide a larger uniformity of the flow field. It creates high resistance to the wind and lowers the velocity down almost to zero close to surface. At side surface, reduction of wind speed can raise up the pressure from suction force to neutral.

3. Analysis and Design Choices

3.1 Problems and Solutions

From previous chapter, it can be indicated that each side of the building handle different type of loads according to the approach direction of the wind. However, there are also solutions to prevent or reduce the effect from each load by using surface shape or its roughness.

3.1.1 Front façade

<u>Load Types</u>: Positive pressure that is depended on wind direction. In most building shapes, center of the impact area has the highest pressure slowly decease to the edge of the side walls and the roof. The location of the pressure is not change during time but there is also some small changes in value.

<u>Solutions</u>: There is no solution from literature study as the research has been done. However, shape of the building has some effect in minimize resistance property from the wind. For example, curve surface is more suitable than the flat one which it can separate the flow better and reduce the pressure in perpendicular to the surface into only small area. Circular shape building is also more flexible in reacting to wind load in different direction.

3.1.2 Side façade

<u>Load Types</u>: Mainly negative pressure which is cause by separation bubble, inverted conical vortex and vortex shedding. The location of under-pressure moves from the back façade to the side and move in the opposite direction of the wind. The negative pressure will stop close to the leading edge (in rectangular shape building) and at the point near the widest section (in circular shape building).

<u>Solutions</u>: If the leading edge can be softened with more than 10% of the building width can reduce the separation bubble and vortices. Roughness on surface can reduce the under-pressure at the façade as well. Different direction of the patterns, horizontal fins and vertical fins give different result but both lead to negative pressure reduction. The horizontal one channelizes the flow which reposition the under-pressure, and the vertical one stops the flow at the surface, however, it can create big friction between close to the surface flow and the flow that is away from the surface.

3.1.3 Back facade

<u>Load Types</u>: Pull force according to the separation area. From CFD analysis the negative pressure (suction) start at the center of the back façade and divide into two parts and move to side façade. The along-wind load from pull force happens suddenly at the moment the wind approach the building and the value reduce during times.

Solutions: The solution is to reduce the size of the separation area. The best shape should be like streamlined symmetric airfoil, which has a very long tail at the back to allow the flow to move along the surface and create least separation area possible. The solution in roughness field can be done by method of golf ball by adding specific type of roughness that contains air gaps. It should create enough turbulence to be able to drag down the flow to be close to the surface, In minimize the problem in this side with surface roughness, circular shape building would be the most suitable one.

3.2 Shape selection

There are several criteria of choosing the building shape such as unpredictable wind direction, drag coefficient (along-wind movement), vortex shedding (cross-wind movement) and possibility in applying adaptive façade system to it.

Firstly, different wind direction can create different effect to building surface. For example, in square shape building 15° angle wind direction to front façade can has result in different location of front positive pressure location, shape and unequal for side façade under-pressure, and the value of drag coefficient. Circular shape building seems to be the shape that is most logical one to receive different wind direction, even though, the value of vortex shedding is high but it could be reduce by additional adaptive façade.

Secondly, wind adaptive façade should be a system that can be added to the building envelope in any side. Even though, there are different wind effects in each side of the façade, the adaptive external envelope can adapt itself to be no matter front, side or back façade according to wind direction. With square building the effect is quite complex to analyze compare to circular shape building which need to be analyzed only in one situation. And it can be possible that with circular shape the adaptive system can be work as one system and it provide more flexibility in flexible façade envelope as will be shown in next topic.

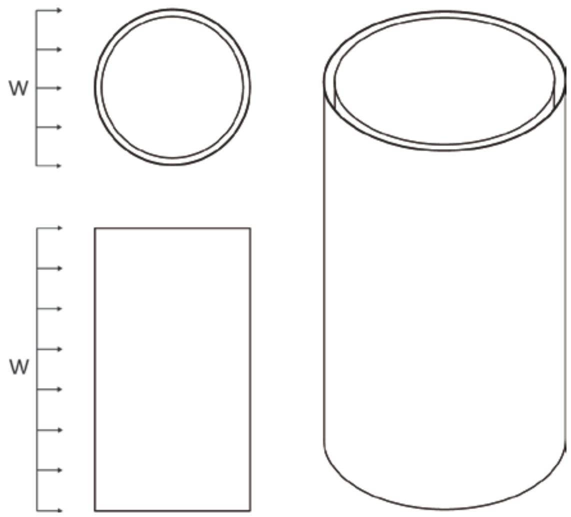
3.3 Possible design choices

After realize wind effect in each building side, several schematic were designed and tested in CFD software to compare the effective of shape and surface roughness in reducing wind effect to the building. At this moment 6 designs were created with different envelope shape and surface but base on a circular shape building. There were compare in term of maximum and minimum surface pressure, peak velocity, drag force (aerodynamic property) and change in location of under-pressure areas. Furthermore, some assumption would be made in term of material used, difficulty in construction (technology requirement which relate to construction cost), maintenance, mechanical and energy requirement and user comfort.

The analysis was done in Autodesk Flow Design because it has quick analysis and can give the overall value in couple of minutes. The 7 computer models were made in the same size with 50m for diameter of circular shape building. The analysis was done only in one segment of the building. That is the reason why the models are in 100m tall with both top and bottom parts were at the surface of wind tunnel which stop the air particle to flow over the models.

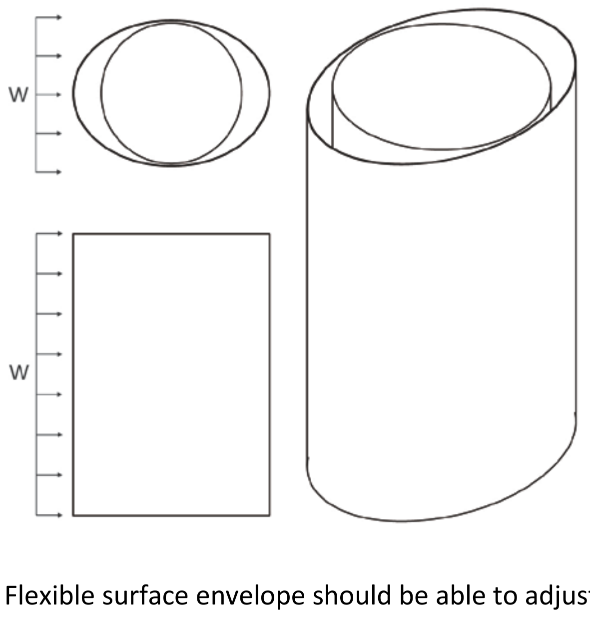
Below are drawings and explanations of each model.

3.3.1 Design 00: Additional inadaptable envelope



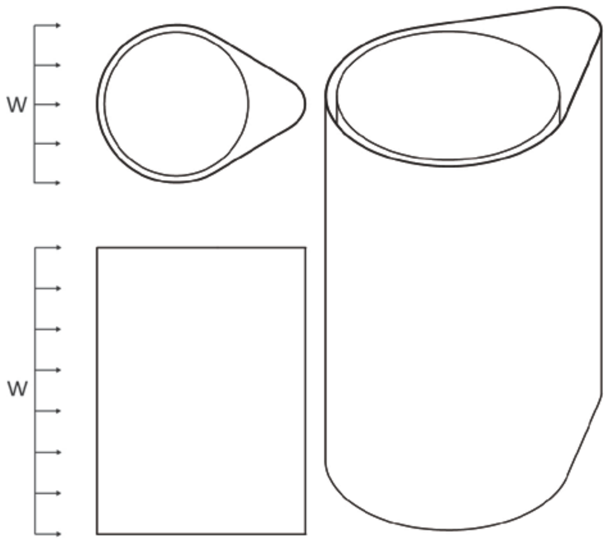
Typical circular envelope model was made as a normal building façade system for comparing with other designs.

3.3.2 Design 01: Shape changing envelope (ellipse shape)



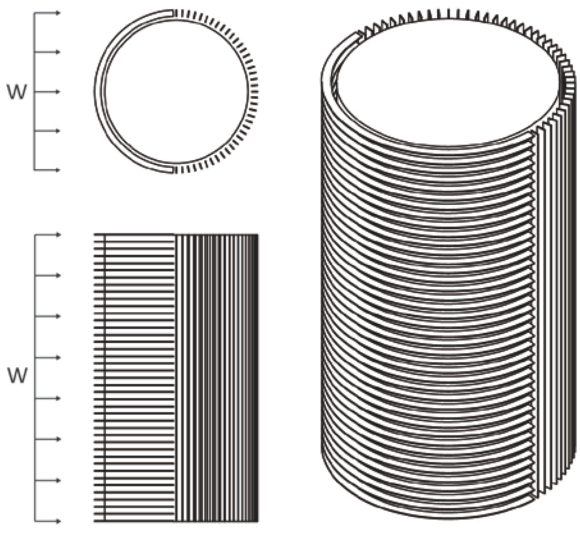
Flexible surface envelope should be able to adjust its shape according to wind direction. The design is similar to EVOLO Tower by (Dr Patrick TEUFFEL, 2007). The design is base on shape changing by reducing wind resistance area and extending the building along wind direction to reduce drag force and separation bubble.

3.3.3 Design 02: Rotatable aerodynamic shape envelope (water drop shape)



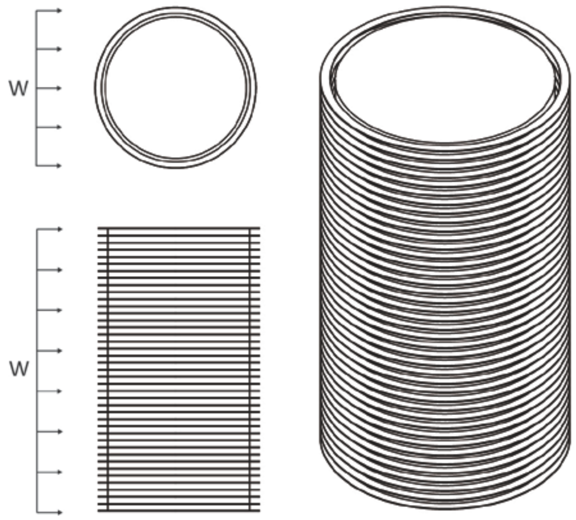
Rotatable envelope with streamline tail was designed to be rotatable with mechanism or with wind flow. The streamline shape was designed to reduce drag force and to make use of wind pressure to turn the tail to the back without energy needed.

3.3.4 Design 03: Adaptable fins outer envelope 1(two directions)



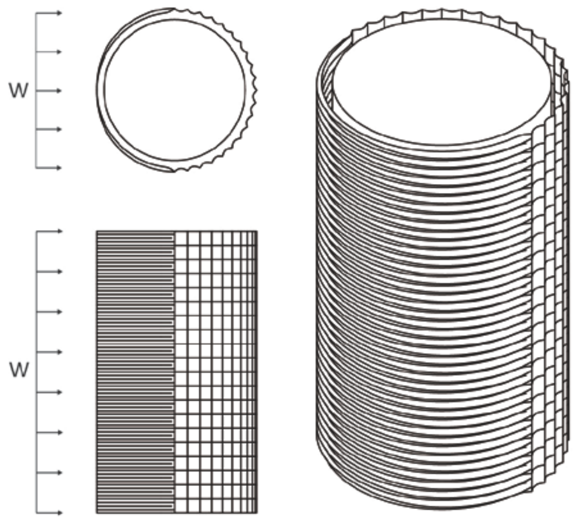
Adaptive fin system was design on surface roughness method. It consists of many small elements. In this case, front façade is protected by horizontal fins to channeling the flow, prevent vortex and slower the velocity. With slower velocity, back façade which is placed by vertical fins work better to draw the laminar flow closer to the surface and reduce the size of separation area and drag force.

3.3.5 Design 04: Adaptable fins outer envelope 2 (horizontal direction)



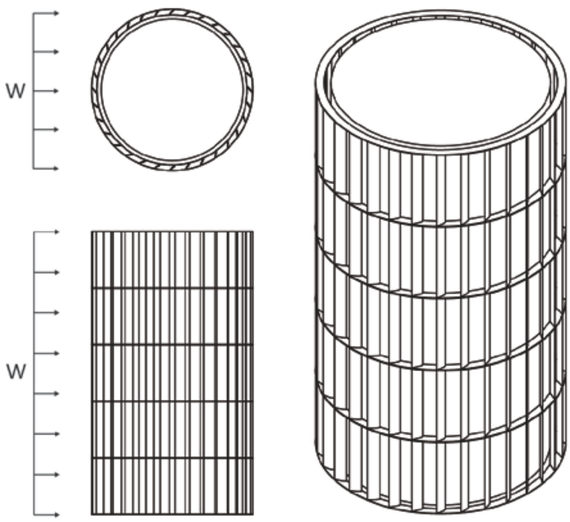
Similar model to "design 03" with only horizontal fins in both front and back façade was made to prove that in any surface pattern, it can create turbulence and draw the flow close to the back façade.

3.3.6 Design 05: Adaptable surface roughness by using membrane



The design was follow "design 03" but the whole surface is covered with membrane that will change the direction of roughness according to wind direction. The membrane surface should be able to create a better flow close to the surface that can reduce its friction.

3.3.7 Design 07: Vertical axis wind turbine envelope



This method was based on transforming energy in the flow to create a useful kinetic energy. The wind will create movement in the turbines which possibly prevent direct pressure to the inner surface and the turbine can be used for electricity production. However, the system was predicted to create torsion to building structure which might be able to reduce the value down by different rotational direction in each turbine. Other than that, rotating turbine can create different air pressure between both of side facades and create a push from one side of the building. And it can create vibration which reduces user comfort.

*Note that with Autodesk Flow Design cannot be used to analyze dynamic or moving element which in “design 07” case, it was done as normal model without any movement.

3.4 Design choices comparison

Table 3.1 shows the result from CFD analysis in different building envelope. The black triangle in positive and negative peak pressure, highest velocity and drag coefficient columns indicate the development of the values during 16 second. Development of negative pressure is the column that shows the location transition of the area on the surfaces that occur to have under-pressure (negative value). The comparison at the left side of the table defines which system is the most suitable one. The selection will be done from the comparison by exclude “design 00” because it is a normal envelope.

The result shows that design 03 and 04 are the most suitable option. They can reduce drag force more than 90% compare to design 00 which is the normal building envelope. Design 03 and 04 should be the best candidates in the further study.

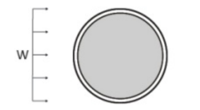
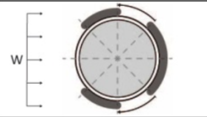
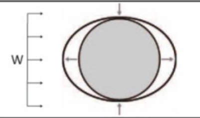
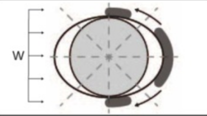
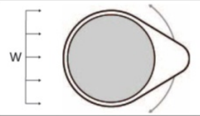
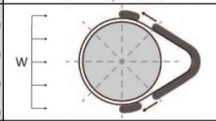
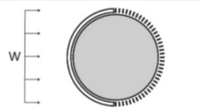
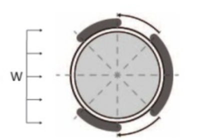
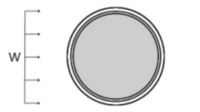
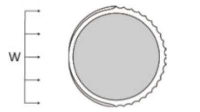
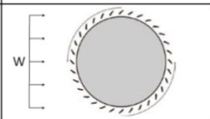
System	Design	Testing time (00.00 minute)	Possitive peak pressure (pa)	Negative peak pressure (pa)	Highest velocity (m/s)	Drag coefficient	Development of negative pressure	Aerodynamic property	Material cost	Construction difficulty	Maintenance aspect	Mechanical requirement	Energy requirement	User disturbance	Note
			Result						Assumption						
0 Circular building with second skin		00.04	724.131	-1002.685	63.427	2.250		I	IIIIIII	IIIIIII	IIIIIII	IIIIIII	IIIII	IIIIIII	
		00.08	795.220	-1234.066	57.663	1.680									
		00.12	847.218	-917.309	50.127	1.830									
		001.6	832.406	-799.699	50.357	1.720									
1 Shape changing envelope		00.04	589.869	-713.649	68.578	1.440		II	IIII	IIII	IIII	IIII	IIII	IIIIII	
		00.08	704.225	-899.610	70.026	1.290									
		00.12	736.986	-1251.849	70.889	1.060									
		001.6	757.348	-1208.508	66.257	1.120									
2 Rotatable aerodynamic shape envelope		00.04	588.204	-830.256	63.731	1.590		IIIII	I	I	I	I	IIIIII	II	- Presume that it is rotated by flow of the wind
		00.08	665.621	-949.792	66.486	1.440									
		00.12	694.376	-1098.631	53.613	0.930									
		001.6	657.007	-1507.728	56.498	0.600									
3 Adaptable fins outer envelope 1 (two directions)		00.04	662.678	-932.782	65.674	0.190		IIIIIII	IIIII	IIIII	IIIII	IIIII	II	III	
		00.08	790.809	-1239.290	60.053	0.140									
		00.12	839.304	-888.135	49.734	0.140									
		001.6	822.325	-775.536	50.253	0.130									
4 Adaptable fins outer envelope 2 (horizontal directions)		00.04	694.525	-790.782	82.919	0.200		IIIIII	IIIIII	IIIIII	IIIIII	IIIIII	III	IIII	
		00.08	879.972	-1228.723	79.939	0.180									
		00.12	845.762	-1063.581	69.424	0.140									
		001.6	862.510	-941.902	69.382	0.140									
5 Adaptable surface roughness by using membrane		00.04	671.297	-940.604	71.098	1.920		III	II	III	III	III	I	IIIII	
		00.08	804.011	-1183.865	60.039	1.550									
		00.12	824.068	-1115.886	49.937	1.400									
		001.6	834.649	-903.878	49.643	1.480									
6 Virtical axis wind turbine envelope		00.04	662.352	-933.667	65.486	1.280		IIII	III	II	II	II	IIIIIII	I	- the analysis has been done without moving components - might be able to produce energy
		00.08	790.073	-1206.572	58.593	0.980									
		00.12	841.876	-943.068	50.680	1.050									
		001.6	817.566	-991.029	50.467	0.950									
								more (I) means better aerodynamic property	more (I) means cheaper	more (I) means easy to be built	more (I) means less maintenace	more (I) means less technology	more (I) means low energy needed	more (I) means more comfort	

Table 3.1: Design choices comparison (bigger size can be seen in Appendix 1)

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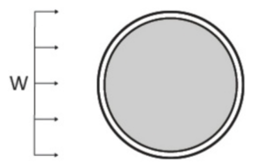
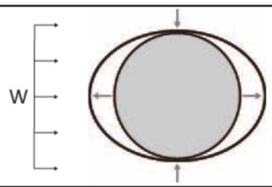
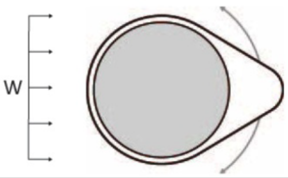
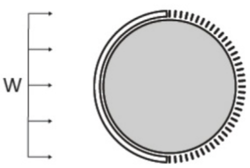
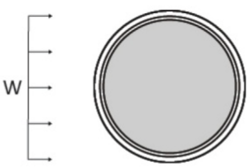
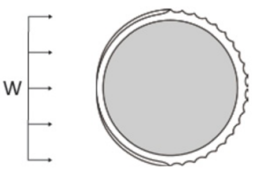
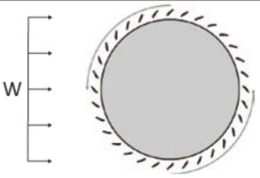
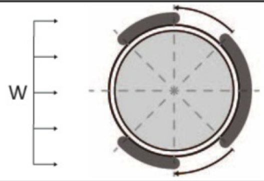
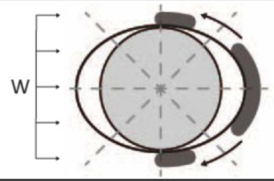
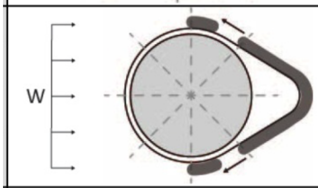
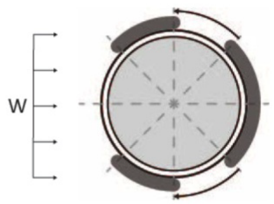
Appendix 1

Design choices comparison

System	Design	Testing time (00.00 minute)	Result: Possitive peak pressure (pa)	Negative peak pressure (pa)	Highest velocity (m/s)	Drag coefficient
0 Circular building with second skin		00.04	724.131	-1002.685	63.427	2.250
		00.08	795.220	-1234.066	57.663	1.680
		00.12	847.218	-917.309	50.127	1.830
		001.6	832.406	-799.699	50.357	1.720
1 Shape changing envelope		00.04	589.869	-713.649	68.578	1.440
		00.08	704.225	-899.610	70.026	1.290
		00.12	736.986	-1251.849	70.889	1.060
		001.6	757.348	-1208.508	66.257	1.120
2 Rotatable aerodynamic shape envelope		00.04	588.204	-830.256	63.731	1.590
		00.08	665.621	-949.792	66.486	1.440
		00.12	694.376	-1098.631	53.613	0.930
		001.6	657.007	-1507.728	56.498	0.600
3 Adaptable fins outer envelope 1 (two directions)		00.04	662.678	-932.782	65.674	0.190
		00.08	790.809	-1239.290	60.053	0.140
		00.12	839.304	-888.135	49.734	0.140
		001.6	822.325	-775.536	50.253	0.130
4 Adaptable fins outer envelope 2 (horizontal directions)		00.04	694.525	-790.782	82.919	0.200
		00.08	879.972	-1228.723	79.939	0.180
		00.12	845.762	-1063.581	69.424	0.140
		001.6	862.510	-941.902	69.382	0.140
5 Adaptable surface roughness by using membrane		00.04	671.297	-940.604	71.098	1.920
		00.08	804.011	-1183.865	60.039	1.550
		00.12	824.068	-1115.886	49.937	1.400
		001.6	834.649	-903.878	49.643	1.480
6 Virtical axis wind turbine envelope		00.04	662.352	-933.667	65.486	1.280
		00.08	790.073	-1206.572	58.593	0.980
		00.12	841.876	-943.068	50.680	1.050
		001.6	817.566	-991.029	50.467	0.950

	Assumption							
Development of negative pressure	Aerodynamic property	Material cost	Construction difficulty	Maintenance aspect	Mechanical requirement	Energy requirement	User disturbance	Note
	I	IIIIIII	IIIIIII	IIIIIII	IIIIIII	IIIII	IIIIIII	
	II	IIII	IIII	IIII	IIII	IIII	IIIIII	
	IIIII	I	I	I	I	IIIIII	II	- Presume that it is rotated by flow of the wind
	IIIIIII	IIIII	IIIII	IIIII	IIIII	II	III	
	IIIIII	IIIIII	IIIIII	IIIIII	IIIIII	III	IIII	
	III	II	III	III	III	I	IIIII	
	IIII	III	II	II	II	IIIIIII	I	- the analysis has been done without moving components - might be able to produce energy
	more (I) means better aerodynamic property	more (I) means cheaper	more (I) means easy to be built	more (I) means less maintenace	more (I) means less technology	more (I) means low energy needed	more (I) means more comfort	

Appendix 2

Draft example building and wind calculation

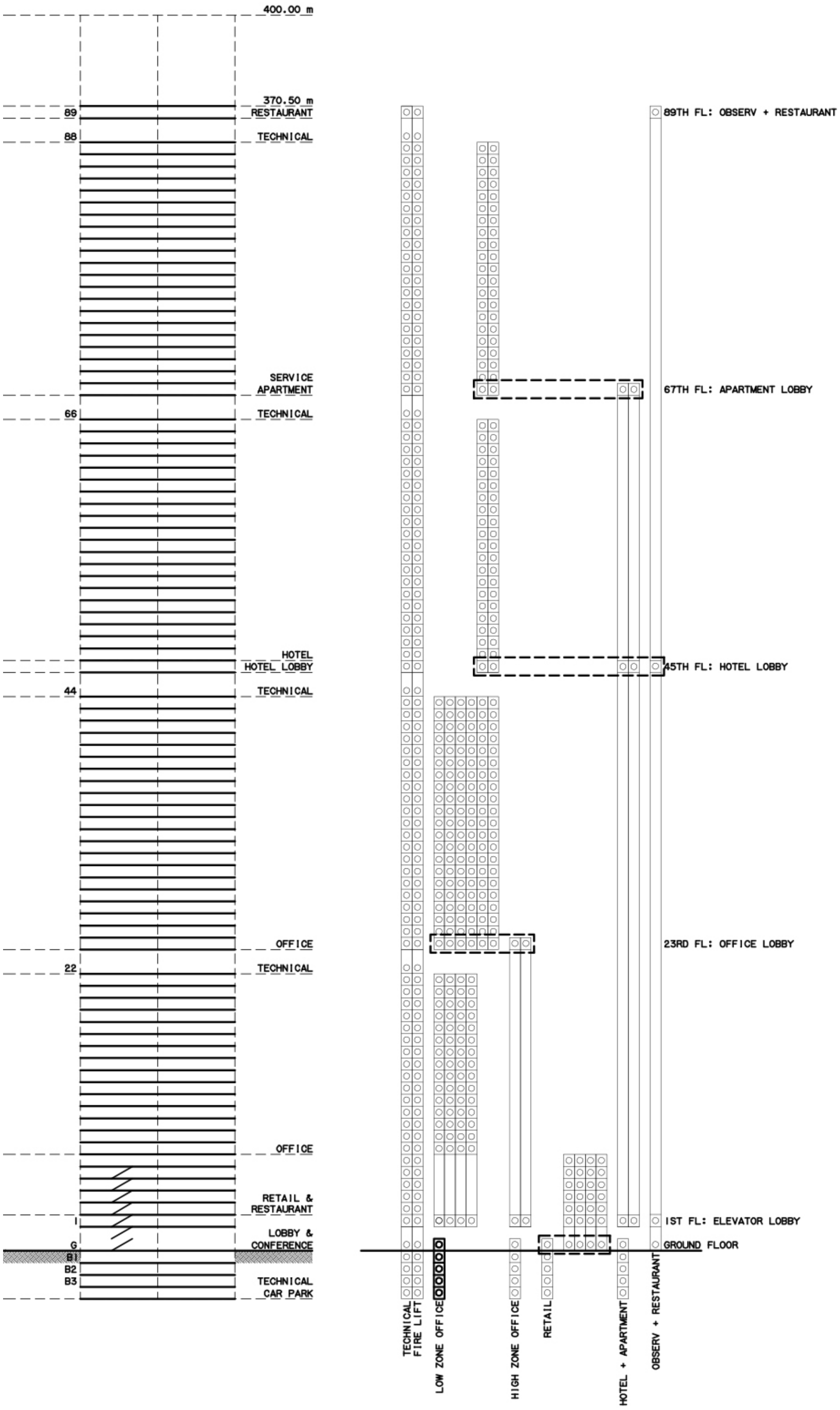


Fig A2.1: Example building draft section and elevators planning. The building is 370.50 m height with 89 stories, 50x50m square shape floor plate.

Wind calculation for example building (Eurocode, 1995)

Fw is the final result

Wind Force (NEN-EN1991-1-4)

Fw=cscd*cf*qp(ze)*Aref		
at 50m	**2091.39009** N/m^2	
at roof	**3767.77899** N/m^2	
or		
Fw=cscd*Σ$_{element}$cf*qp(ze)*Aref		
cscd: structural factor **at 50m**	0.943714502	
cscd: structural factor **at roof**	0.987027169	
cf: force coefficient	1.407	
qp(ze): peak velocity pressure **at 50m**	1575.071667	
qp(ze): peak velocity pressure **at roof**	2713.077598	
Aref:reference area of the structure or structural element=b*h	1 m^2	*reference area for FEM analysis kN/m^2
CsCd=(1+2*kp*Iv(zs)*sqrt((B^2)+(R^2)))/(1+7*Iv(zs))		
at 50m	0.943714502	
at roof	0.987027169	
kp: peak factor defined as the ratio of the maximum value of the fluctuating part of the response to its standard deviation **at 50m**	3.081686338	
kp: peak factor defined as the ratio of the maximum value of the fluctuating part of the response to its standard deviation **at roof**	3.044033046	
Iv: turbulence intensity **at 50m**	0.255622219	
Iv: turbulence intensity **at roof**	0.169065896	
zs: reference height for determining the structural factor		
B^2: background factor, allowing for the lack of full correlation of the pressure on the structure surface **at 50m**	0.163154775	
B^2: background factor, allowing for the lack of full correlation of the pressure on the structure surface **at roof**	0.429909674	
R^2: resonance response factor, allowing for turbulence in resonance with the vibration mode **at 50m**	0.910328573	
R^2: resonance response factor, allowing for turbulence in resonance with the vibration mode **at roof**	0.8295817	
kp=sqrt(2*ln(v*T))+0.6/sqrt(2*ln(v*T))		
at 50m	3.081686338	
at roof	3.044033046	
T: averaging time for the mean wind velocity, T = 600 seconds	600 second	
v: up-crossing frequency given in (4)		
v=n1,x*sqrt((R^2)/((B^2)+(R^2))) : v≥0.08 Hz		
at 50m	0.103276635	
at roof	0.091969209	
n1,x: natural frequency of the structure, which may be determined using Annex F.		
B^2=1/(1+0.9*((b+h)/(L(zs))))^0.63		
At 50m	0.405299865	
At roof	0.682284978	
B^2=1/(1+(3/2)*√(((b/L(zs))^2)+((h/(L(zs)))^2)+(((b/L(zs))*(h/L(zs)))^2))		
B^2 at 50m	**0.163154775**	
B^2 at roof	**0.429909674**	
b, h: width and height of the structure, see Figure 6.1	420.5 m	
b	50 m	
h	370.5 m	
L(zs): turbulent length at 50m	118.5061968	
L(zs): turbulent length at roof	453.4394062	
L(z)=Lt*(z/zt)^α : z>zmin		
At 50m	**118.5061968**	
At roof	**453.4394062**	
zt=200m	200 m	
Lt=300m	300 m	
α=0.67+0.05*ln(z0)	0.67	
R^2=(π^2)/(2*δ)*SL(zs,n1,x)*Ks(n1,x)		
at 50m	0.910328573	
at roof	0.8295817	
δ: total logarithmic decrement of damping given in F.5		
at 50m	0.091750813	
at roof	0.097101948	
SL: non-dimensional power spectral density function given in B. 1 (2)		
at 50m	0.171087608	
at roof	0.110739173	
Ks: size reduction function given in (5).		
at 50m	0.098848539	
at roof	0.147287722	

*note: Red texts are where in NEN-EN1991-1-4 that the values come from

SL(z,n)=n*sv(z,n)/(δv^2)		
SlL(z,n)=(6.8*fL(z,n))/((1+10.2*fL(z,n))^(5/3))		
at 50m	0.171087608	
at roof	0.110739173	
fL(z,n): non-dimensional frequency determined by the frequency n = n1,x,		
fL(z,n)=n*L(z)/(vm(z))		
at 50m	**0.469307477**	
at roof	**1.18766261**	
δ=δs+δa+δd		
at 50m	**0.091750813**	
at roof	**0.097101948**	
δs: logarithmic decrement of structural damping	0.08	*NEN-EN-1991-1-4 Table F.2 (mixed structures concrete + steel)
δa: logarithmic decrement of aerodynamic damping for the fundamental mode		
at 50m	0.011750813	
at roof	0.017101948	
δd: logarithmic decrement of damping due to special devices (tuned mass dampers, sloshing tanks etc.)	0	*no damping device
δa=cf*ρ*vm(zs)/(2*n1*μe)		
at 50m	**0.011750813**	
at roof	**0.017101948**	
cf: force coefficient	1.407	
ρ density of air at 50m	1.149	
ρ density of air at roof	1.106	
vm(zs) at 50m	31.35113057	
vm(zs) at roof	47.40190495	
n=46/h : fundamental frequency of along wind vibration	0.124156545 Hz	
μe: equivalent mass per unit area of the structure which for rectangular areas given by Expression (F.17).	17370	
μe=ρb*d	17370	
ρb: volumetric mass of the building (kg/m^3)	347.4 kg/m^3	???
Ks(n)=1/(1+sqrt((Gy*φy)^2+(Gz*φz)^2+(2/(22/7)*Gy*φy*Gz*φz)^2)		
at 50m	**0.098848539**	
at roof	**0.147287722**	
Gy=5/18	0.277777778	*NEN-EN-1991-1-4 Table C.1
Gz=1/2	0.5	*NEN-EN-1991-1-4 Table C.1
φy=(cy*b*n)/(vm(zs))		
at 50m	2.277111294	
at roof	1.506057902	
φz=(cz*h*n)/(vm(zs))		
at 50m	16.87339469	
at roof	11.15988905	
cy,cz: decay constants	11.5	*NEN-EN-1991-1-4 Page 109
vm(zs) at 50m	31.35113057	
vm(zs) at roof	47.40190495	
n=46/h : fundamental frequency of along wind vibration	**0.124156545** Hz	
cf= cf;0*ψr*ψλ	**1.407**	*different formular with different shape
cf,0: force coefficient of rectangular sections with sharp corners and without free-end flow	2.1	* NEN-EN 1991-1-4 figure 7.23
ψr: reduction factor for square sections with rounded corners. Ψr depends on Reynolds number	1	* NEN-EN 1991-1-4 figure 7.24
ψλ: end-effect factor for elements with free-end flow	0.67	* NEN-EN 1991-1-4 table 7.16 & figure 7.36

*note: Red texts are where in NEN-EN1991-1-4 that the values come from

qp(z)=((1+7*Iv(z))*ρ*vm(z)^2)/2		
qp(z)=ce(z)*qb		
at 50m	**1575.071667**	
at roof	**2713.077598**	
ρ: air density, which depends on the altitude, temperature and barometric pressure to be expected in the region during wind storms		*http://www.denysschen.com/catalogue/density.aspx
at 50 m (kg/m^3)	1.149	
at roof (kg/m^3)	1.106	
Iv: turbulence intensity		
ce(z): exposure factor		
qb: basic velocity pressure		
vm(z): mean wind velocity calculated at the height 50m	31.35113057	
vm(z): mean wind velocity calculated at the roof	47.40190495	
qb=(ρ*vm(z)^2)/2		
Iv(z)=σv/(vm(z))		
Iv(z)=kl/(co(z)*ln(z/z0))		
Iv(z) at 50m	**0.255622219**	
Iv(z) at roof	**0.169065896**	
σv=kr*vb*kl		
kI: turbulence factor. The value of kI may be given in the National Annex. The recommended value for kI is 1,0.	1	
<u>Variation with height</u>		
Vm(z)=cr(z)*co(z)*vb		
At 50 m	**31.35113057** m/s	
At roof	**47.40190495** m/s	
vb: basic wind velocity (hongkong) (m/s)	34.2	
cr(z): roughness factor at 50 m	0.916699724	
cr(z): roughness factor at roof	1.386020612	
co(z): orography factor, taken as 1,0 unless otherwise specified in 4.3.3	1	
cr(z)=kr*ln(z/z0)		
At 50 m	**0.916699724**	
At roof	**1.386020612**	
z0: roughness length (category IV : NEN-EN 1991-1-4)	1	
Category IV: Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m		
zmin = 10 m (category IV : NEN-EN 1991-1-4)		
z: height(m) at the same length with width (at 50 m)	50 m	
z: height(m) (at roof = 370.5 m)	370.5 m	
kr: terrain factor depending on the roughness length z0 calculated using		
kr=0.19*(z0/z0.11)^0.07	**0.234328817**	
z0,II = 0,05 m (terrain category II, Table 4.1)	0.05	

*note: Red texts are where in NEN-EN1991-1-4 that the values come from