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ABSTRACT

During the last century, there has been a huge development in the field of wind engineering. Wind tunnel testing in combination with CFD has made it possible for engineers to build tall irregular buildings. Today, Burj Khalifa serves as a monument of what is possible to achieve within engineering.

Wind load is an important factor in structural analysis. Storms and bad weather result in severe damages to buildings and structures, causing great economic losses every year. To ensure proper durability, habitability and safety measures, different sets of codes and standards are developed and implemented worldwide. The governing wind load for a tall building is the along-wind. However, in some cases across-wind exceeds the along-wind due to fluctuations caused by the vortex shedding phenomena. Hence, these factors need to be investigated during the designing stage of tall buildings. The most commonly strategy to suppress these loads are by doing architectural modifications such as tapering, setback, openings, twisting and corner softening/cutouts.

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Stavanger, May 12, 2021

Anders R. Meltveit   Tor André Stangeland

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ABBREVIATIONS

AMD	Active Mass Damper
AVSD	Active Variable Device
CFD	Computational Fluid Dynamics
C_p	(Wind) Pressure Coefficient
CTBUH	Council on Tall Buildings and Urban Habitat
CWE	Computational Wind Engineering
HFBB	High-frequency Base Balance
HFPI	High-frequency Pressure Integration
LES	Large Eddy Simulations
NASA	National Aeronautics and Space Administration
RANS	Reynolds-Averaged Navier-Stokes
TMD	Tuned Mass Damper
UNDRR	United Nations Office for Disaster Risk Reduction
URANS	Unsteady Reynolds-Averaged Navier-Stokes
VD	Viscous Damper

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CHAPTER 1

INTRODUCTION

1.1 Aim of study

The aim of this bachelor thesis is to provide a simplified understanding of the field within wind engineering for tall buildings and methods to reduce wind response of tall buildings.

1.2 Objectives of study

The thesis comprises a literature study on wind engineering of tall buildings. By performing a literature review and comparing different research outcomes, an attempt to make a simplified overview of the application of wind tunnel, computational fluid dynamic (CFD) and benefits related to architectural modifications providing more aerodynamic buildings.

1.3 Methodology

The thesis is strictly a literature study. Thus, mainly published literature was used to gain knowledge. The online search engines Oria and Google were the main sources to acquire articles and books.

1.4 Background

Through the years, architectural design of tall buildings has become more modernistic, and by that, more irregular in geometry. This makes calculation of wind loads highly complicated. Wind load calculation is a highly important factor in structural analysis. Storms and bad weather result in severe damages to buildings, causing tremendous economic losses every year. Therefore, accurate calculation of wind load is one of the key components in the designing stage. Through testing and analyses of models, structural weaknesses can be detected and adjusted for before continuing to construction stage. This provides safer buildings, as well as reduction in material costs. To ensure proper durability, serviceability and safety measures, different sets of building codes are utilized around the world. The calculation methods given by Eurocode and other international standards are only valid for buildings of regular shape and up to 200 meters in height. To acquire pressure coefficients for irregular shaped buildings, it is required to simulate wind conditions using wind tunnels and/or advanced computer software. Such tools assist in the calculations of wind loads. Nevertheless, it is still important that the user understands the significance of required input data. As tall buildings are becoming more and more common worldwide, the need for more precise wind load data is increasing. Thus, there has been increasing numbers of studies on the wind response of tall buildings, in recent decades. Studies on the effect of aerodynamic modifications of tall buildings to mitigate the imposed wind loads, show that such modifications will result in better building performance regarding wind excitation.

1.5 Assumptions, challenges and limitations

During all research, there is a risk and possibility of errors and insufficiencies. This is particularly true regarding something as complex as wind. The chaotic nature of wind makes it a challenge to precisely predict and calculate wind actions. There are many important equations and concepts to consider in the technical field of wind engineering. As this thesis is only on bachelor level, the authors will not go into mathematical equations and the advanced technicalities of analyzes applied in the reviewed studies herein.

The authors would also like to emphasize that the studies reviewed herein, use various configurations regarding wind tunnel and CFD simulations (e.g. terrain category, building model characteristics, software packages, etc.). This hampers precise comparison of results. Thus, conclusions from each study only apply under the specific conditions of that particular study.

CHAPTER 2

THE NATURE OF WIND

2.1 Wind formation

Wind is the movement of air relative to the earth. The nature of wind is chaotic, and its speed varies at any given time. In general, the wind speed will increase with increasing height (Fig. 2.1). The driving force is mainly air pressure differences, stemming from the non-uniform solar heating of the Earth’s surface. The Earth’s poles receive less solar heating compared to the Equator. This uneven solar heating leads to the formation of convection currents [1].

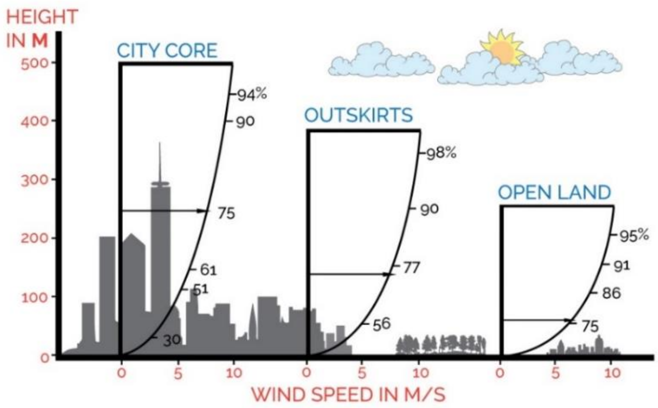


Figure 2.1: Wind speed as a function of terrain roughness. The wind speed increases with increasing height (Figure courtesy of the Sinovoltaics Group).

In each hemisphere, the wind circulates in three distinct cells (Fig. 2.2). Forces generated by Earth’s rotation also contributes to pressure differences. Combined with the rotation of the Earth, large circulation systems are created [1].

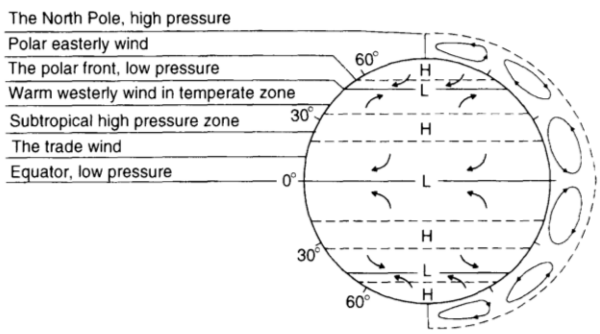


Figure 2.2: The convection cells on the northern and southern hemisphere. The sketched cells are not to scale, as the radial direction is strongly exaggerated. The air flows up to a maximum of 15 km from the Earth’s surface, representing less than 1/10 mm in the sketch [1].

The pressure gradient (drop in pressure per horizontal unit length) determines the wind speed. Air flows from areas of high pressure to areas of lower pressure. If the change in air pressure over a short distance is substantial, strong winds will occur as a result. Most wind induced damages to buildings occur during strong winds. Air flow can be classified into the main flow and the boundary layer flow. Within the main flow the viscosity (fluid friction) plays an insignificant part. While friction greatly affects the air flow in the boundary layer flow. The troposphere is the closest layer of the atmosphere encircling the Earth. It extends from Earth's surface to an average altitude of 11 km. Nearest to the surface is the atmospheric boundary layer (ABL) and comprises the part of the troposphere that is influenced by the Earth's surface. After the ABL follows the "free atmosphere". Here, the wind acts approximately geostrophic, as the air flow is not affected by the friction of Earth's surface [2, 3].

2.2 Wind loads

Tall buildings can be considered as flexible structures. The dynamic wind load induced on such structures will result in fluctuating deflections in three principal directions. These are along-wind, across-wind, and torsional deflections (Fig. 2.3) [2].

Tall buildings must be able to resist not only gravity loads, but also lateral loads. These are the results from wind, earthquakes, settling etc. Tall buildings are highly susceptible to lateral loads as they act like cantilevers. As their height-to-base ratio increases, they become even more susceptible to wind load. Several factors influence the building's response to wind. These are: (1) The nature and characteristics of the wind. (2) The size and geometry of the building. (3) The building's orientation with respect to the prevailing direction of the wind. (4) The flexibleness/stiffness of the building (5) The building's distribution of mass. (6) The degree of damping of the structural system and construction material. (7) Effects from surrounding topography (e.g. neighboring buildings, etc.) [2].

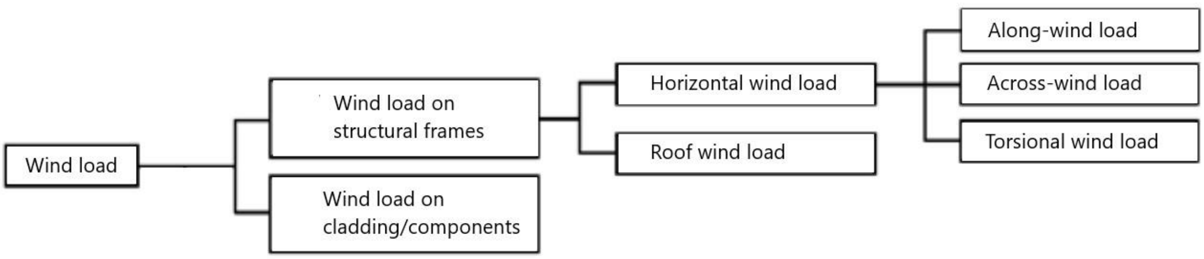


Figure 2.3: Wind load classification.

2.2.1 Along-wind load

Along-wind force (Fig. 2.4) is the force working in the prevailing wind direction. The wind load actions from the along-wind will occur on windward side as pushing force and at leeward side as suction force [4].

2.2.2 Across-wind load

Across-wind (Fig. 2.4) develops as a response of the building's interaction with the along-wind. The across-wind usually have the same magnitude as the along-wind. However, in some cases it exceeds the along-wind magnitude due to fluctuations in turbulent flow caused by the vortex shedding phenomena [4, 5].

2.2.3 Wind induced torsion

Torsion (Fig. 2.4) is caused due to inequality in pressures on the different faces of a building [4].

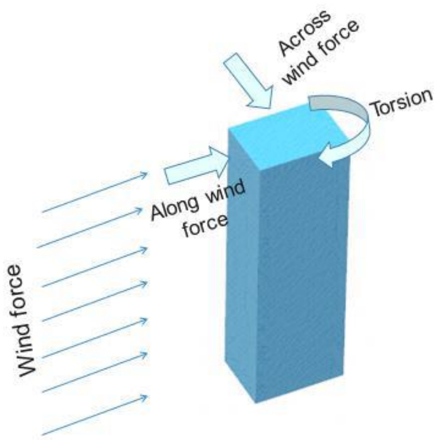


Figure 2.4: The components involved during wind excitation upon a tall building [94]. Along-wind in the same direction as the wind direction (windward side), continuing over building to leeward side. Along-wind causes drag forces. Across-wind force works in horizontal direction to the direction of the along-wind force. Across-wind causes lifting forces. Wind induced torsion may affect the serviceability of a building, hence it needs to be accounted for in the designing stage [6].

2.2.4 Vortex shedding

Vortex shedding occurs when air passes a structure with high velocity. The air then changes directions causing low – pressure vortices on the back of the structure (Fig. 2.5). If the vorticity reaches the same frequency as the natural frequency of the structure, the structure will start to sway. This may cause damages to the structure or lead to total failure (Fig. 2.6) [7].

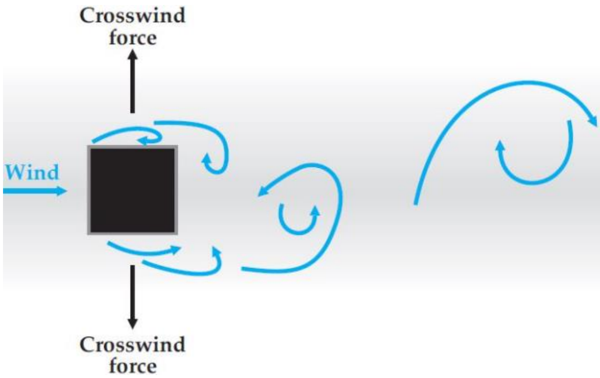


Figure 2.5: Vortex shedding. Wind hits structure and creates low- pressure vortices on back of structure (i.e. creating suction force at leeward side) [8].

Figure 2.6: Tacoma Narrows Bridge collapsing in 1940, due to oscillation caused by vortex shedding. Only 4 months after opening [9].

Deciding appropriate design wind speed is a vital first task when calculating the design wind loads for structures. There are often uncertainties regarding this part of the design process, as statistical analysis of recorded wind speeds is needed [2]. Peak velocities representing very high frequent fluctuations are not occurring simultaneously over large areas. This is because high frequent fluctuations are caused by eddies [1]. Eddies are whirls of air, created on leeward side when air flows hit a solid object. Gust size varies across and along wind direction, and vertically. Wind codes apply general approximations when trying to describe this chaotic nature. Hence, overdimensioning often occurs when wind load calculations are based entirely on peak velocities over the whole structure [1].

Palutikof *et al.* [10] reviewed the various methodologies for predicting extreme wind speeds. Careful estimation of the occurrence of extreme wind speed should be carried out to achieve proper dimensioning. These estimates are often expressed by maximum wind speed X_T exceeded, on average once every T years, the return period, R [64]. Normally, when applying wind data, estimates of a 50-year return period gust or wind speed are needed. However, often the recorded wind data does not date back this far. When this is the case, the wind data are often fitted to a theoretical distribution.

Davenport [11, 12, 13] introduced the concept of the wind load chain (Fig. 2.7). Each link represents a step during wind load calculation. The chain concept symbolizes that the whole design process is only as precise as the weakest, least accurate task performed by the wind engineer. It also shows a relation between the interconnected links [14].

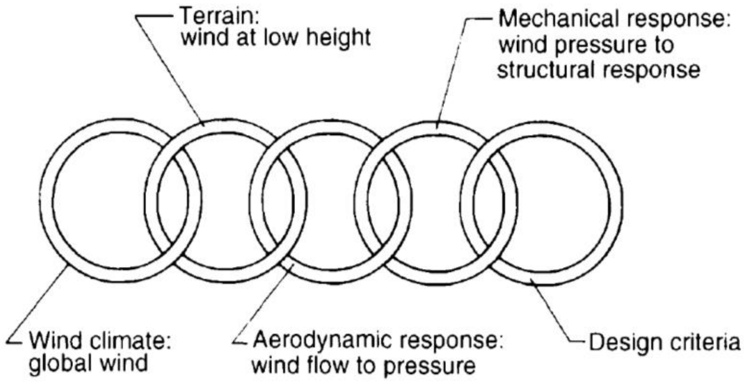


Figure 2.7: The wind load chain. Each link represents a step undertaken during calculation of wind actions [14]. Each link also treats random parameters, hence statistical methods are recommended when dealing with these steps.

2.3 Wind pressure coefficient

Wind pressure coefficients (C_p) are non-dimensional quantities. They are dependent on the geometry of the affected body, and the characteristics of the air flow [2]. The wind pressure coefficient at any given point is defined as the wind pressure at that point divided by the dynamic pressure in free wind at a reference height above ground (normally 10 meters) [15].

$$C_{px} = \frac{P_x - P_0}{P_d} \tag{1}$$

$$P_d = \frac{\rho * U^2}{2} \tag{2}$$

C_{px} = wind pressure coefficient at any point

P_x = static pressure (Pa) at point x on the façade

P_0 = static reference pressure (Pa) at 10-meter height

P_d = dynamic pressure (Pa)

ρ = air density (kg/m^3)

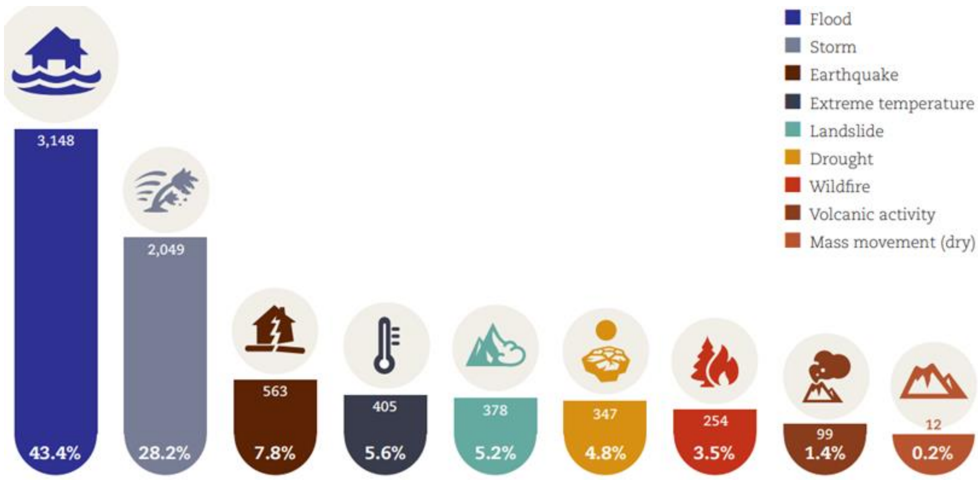
U = wind speed (m/s) at 10-meter height

C_p can be estimated by three different methods: using wind tunnels to test models, by full-scale testing, and by applying parametric equations achieved from experiments [16]. To acquire accurate estimations of C_p for a specific building, either full-scale testing [17, 18] or a model test is required [19, 20]. This is time consuming and expensive. Thus, wind pressure coefficients used in practice, have usually been obtained by other wind engineers at an earlier time by testing models of various structures in wind tunnels [21]. Wind pressure coefficients commonly give the average pressure or suction on the surface of a structure.

The sources to obtain C_p data can be divided into two sources: primary and secondary sources [16]. Primary sources of C_p data are obtained directly from a specific building and most of the variables impacting the data are taken into consideration. Numerous sources of secondary sources exist, and they are generated based on primary sources. C_p data provided by standards are secondary sources, and they present data for a limited set of generic, regular shaped building configurations [16].

2.4 Nature catastrophes

Report [36] from the United Nations Office for Disaster Risk Reduction (UNDRR) from 1998-2017 (20-year period) revealed that wind accounted for roughly 30% of the nature catastrophes (Fig. 2.8). Wind related catastrophes also affected about 726 million people in this period. On average, close to 37 million people each year.



2.8: Numbers of nature catastrophes, 1998-2017 (Figure courtesy of UNDRR).

It was also noted in the report that 1.3 million people between 1998-2017 lost their lives due to nature catastrophes. Of this, nearly 233 000 (17%) died in disasters related to wind (Fig. 2.9). On average, 11 600 annual deaths. Earthquake caused most deaths, accounting for almost 60%.

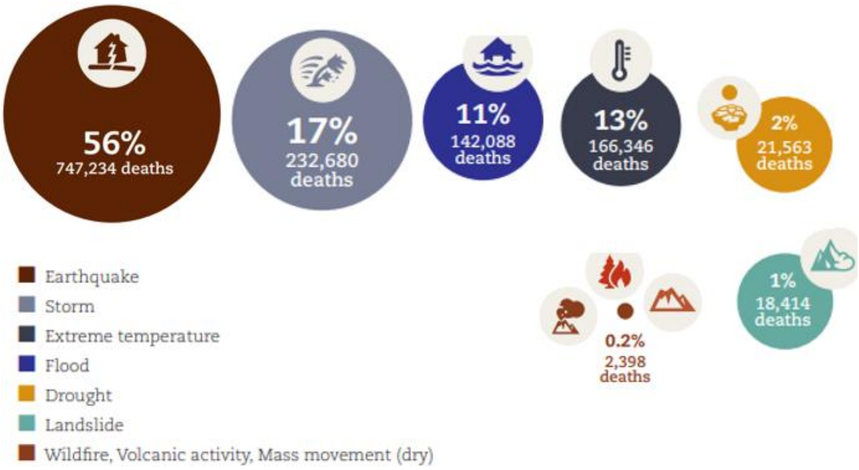


Figure 2.9: Numbers of deaths, 1998-2017 (Figure courtesy of UNDRR).

Economic losses from 1998-2017 were recorded to be 2908 billion dollars. Wind alone accounted for nearly 50% of these losses (Fig. 2.10).

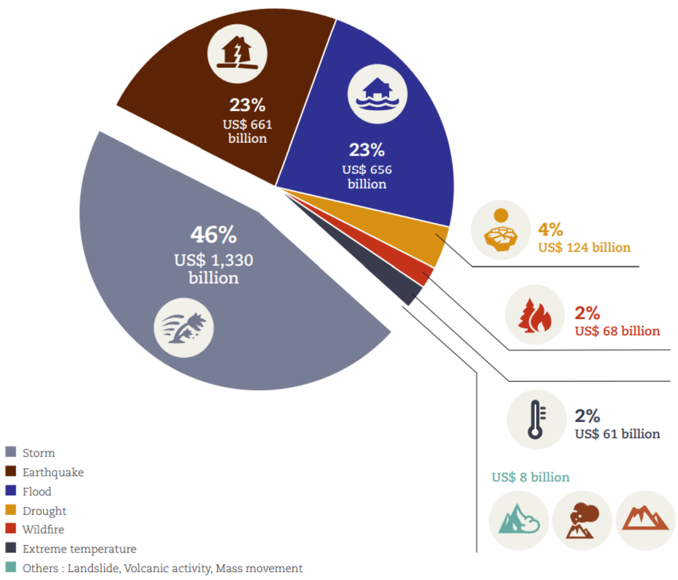


Figure 2.10: Economic losses, 1998-2017 (Figure courtesy of UNDRR).

CHAPTER 3

PRINCIPLES OF TALL BUILDINGS

3.1 Classification of tall buildings

High-rise buildings are becoming more and more common around the world, as demand for space in densely populated areas is increasing. Recent decades' great advances in engineering technology have allowed for sophisticated, breath-taking high-rise buildings. The terms tall, supertall, megatall (Fig. 3.1), high-rise and skyscraper are often used interchangeably. However, there is no clear definition on what constitutes a tall building, and the term is somewhat subjective. The location of a building will determine whether a building is considered tall. A 15-story building could be considered tall in Europe. However, if the same building is in a high-rise city like New York, the building might not be considered tall at all. The proportion of a building could make it appear tall. Meaning, the building is not very tall but slender, giving the impression of being tall. Additionally, a tall building, but with a very large cross-section might not be considered tall. To be classified as a skyscraper, a building must be self-supporting, and be able to remain standing without requiring tension cables or other supports. Habitable floor space also needs to make up at least 50% of the building's height. The height must be minimum 150 meters [93].

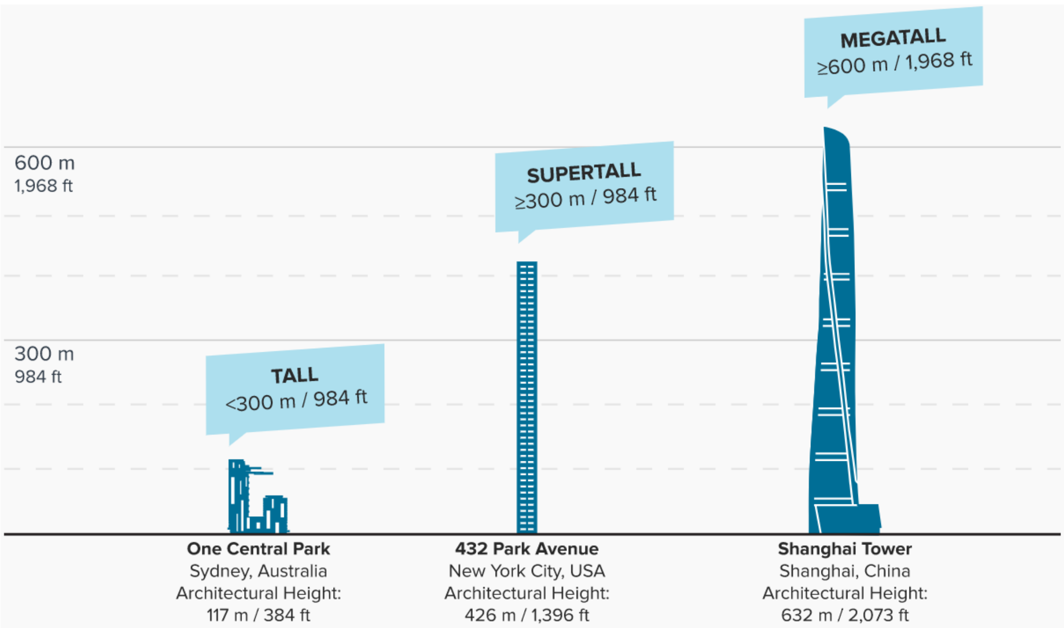


Figure 3.1: The definition of tall buildings by the Council on Tall Buildings and Urban Habitat (CTBUH) [23].

3.2 Aerodynamics of tall buildings

A structure subjected to air flow is subjected to aerodynamic forces. This causes responses such as drag, lifting, torsional moments and bending/flexing [24]. The natural wind is the most significant, unpredictable, and complex force induced on tall buildings. Baby *et al.* [25] defined tall buildings as masts anchored to the ground, bending and swaying in the wind. This lateral displacement (or wind drift), needs to be within adequate limits. Hence, several factors need to be considered during the design phase. Some of these are strength and stiffness requirements, as well as stability regarding lateral deflection caused by wind. This is of vital importance to prevent structural damages and for the occupants' comfort level. Tall buildings can be considered as bluff bodies of medium to high aspect ratio [2]. Fundamental equations describing the nature of air flow are highly complex, as the systems of equations describing the boundary conditions consist of many parameters [14]. When wind hits a structure, e.g. a simple free-standing wall, the air flow on windward side is forced around the edges of the structure.

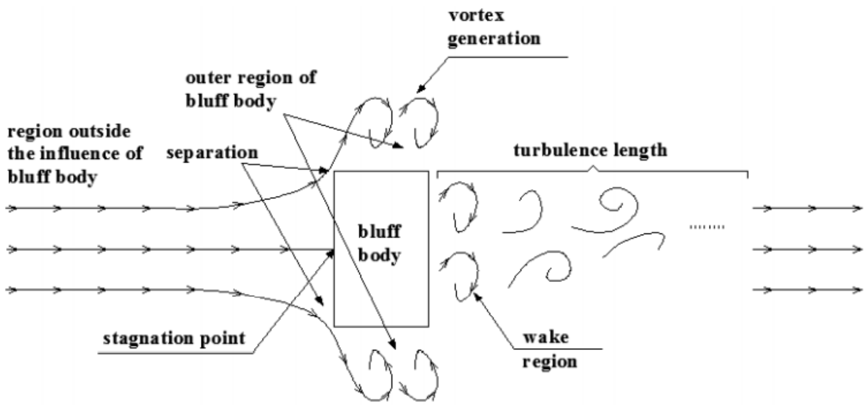


Figure 3.2: Cross-section of tall building with corresponding wind phenomenon resulting from general boundary-layer flow pattern around (figure courtesy of Jack E. Cermak).

The interaction between the structure and the wind changes the magnitude and direction of the wind velocity. This causes changes in the pressure. At, and near the middle of the wall, a stagnation pressure is created. The pressure gradient increases rapidly near the edges. After the wind attacks the wall at a perpendicular angle, the air flow is diverted by the wall and flows along the wall surface in a parallel direction. During this time, the air flow regains its velocity, creating different wind pressure coefficients on the structure surface. On the leeward side of the wall, the distribution of wind pressure coefficients is different. Immediately after flowing around the edges, the inertia of the air flow, causes the air flow to not being able to enclose the structure entirely. The fast-moving air flow coming from around the edges "entraps" air in the lower middle section of the wall. Thus, reducing the pressure and creating suction. This will also occur for larger structures i.e. buildings (Fig. 3.2) [2].

3.3 Purpose of tall buildings

The main purpose of tall buildings is to satisfy the demand of occupancy. In some cases, prestige may play some factor, having the building serve as a status symbol. Thus, the demand by imaginative clients may lead to tall buildings that are architecturally impressive and highly irregular in shape. Tall buildings are utilized for offices, hotel, commercial, residential or mixed purposes (Fig. 3.3).

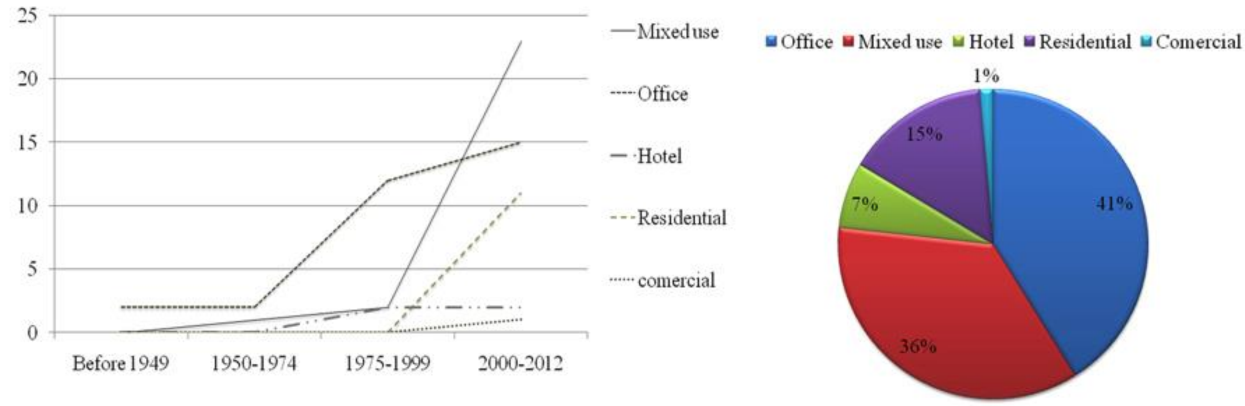


Figure 3.3: Graph of the rate of development of supertall buildings regarding purpose. Pie chart showing todays purpose distribution of supertall buildings [26].

3.4 The building structure

A building can be defined as an enclosed structure which stands permanently in one place and has roof and walls [27]. Tall buildings are typically made up of steel or composite steel-concrete frame structures (Fig. 3.4).

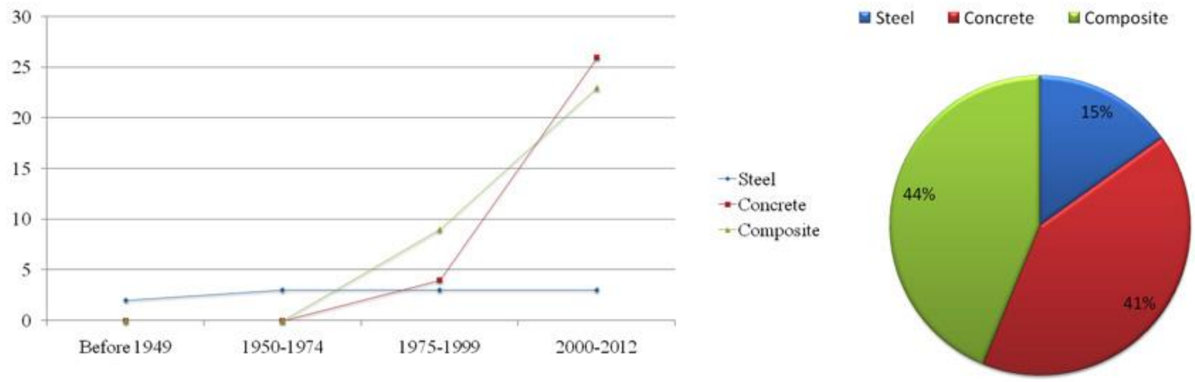


Figure 3.4: Graph of the development rate of the 73 tallest buildings in the world (as of 2012) regarding structural material. Pie chart of the distribution of materials used in the 73 tallest buildings (as of 2012) [26].

Buildings consist of the structure and non-structural elements. The structure comprises the skeleton of structural elements which supports the entire building. The non-structural elements comprise of every element in or on a building other than the structural elements. These are architectural elements (e.g. windows, dropped ceilings, chimneys), building content, and utility/mechanical systems. The structure can be divided into the substructure and the superstructure[28].

3.4.1 The substructure

The substructure is the portion of the building that lies below ground level. It serves to support the structure by receiving the loads from the superstructure and transfer the loads downwards to a load-bearing ground layer. The substructure consists of components like the foundation, bearing walls, girders, etc. The foundation comprises the main portion. At the planning stage of the building, the building site must be surveyed to obtain necessary information about required foundation size. Wrong estimation and construction of the foundation may lead to subsiding or collapse of the building [29].

3.4.2 The superstructure

The superstructure (or structural structure) makes up the portion that serves the main purpose of the structure. This purpose is to enclose and divide space, and to transfer the loads safely down to the substructure. The superstructure comprises the primary, secondary, and finishing elements, and the services [29].

3.4.2.1 The primary elements

The primary elements divide the building into rooms and grant floor-to-floor access. The main primary elements are the walls, floor, roof, and stairs. The walls are divided into external and internal walls [29].

3.4.2.2 External walls

There are different types of external walls used for tall buildings. The facades often consist of curtain or window walls. Curtain walls are self-supporting, nonstructural, glazed wall systems. To install curtain walls cranes are usually used from the outside. The wall system is anchored to overlaying concrete slab. This installation process is complex and expensive. However, curtain walls give high structural integrity, because of fewer joints and mullions required compared to most window wall. Because curtain wall systems act like single units, they are highly wind resistant. Window wall systems are obtained by using the concrete slabs of the building as structural supports and installing glazing in between the slabs. These systems are popular for residential purposes because they allow for windows and balcony doors. They are usually installed from inside the building. This is more efficient, safer, and cost effective compared to curtain wall systems. Curtain and window walls are widely used as they allow for interesting architectural design [30].

3.4.2.3 Internal walls

Internal walls are either load bearing walls or non-load interior walls. Load-bearing walls support loads from the upper floors and roof and transfer loads downwards to the foundation. Non-load bearing walls are raised to divide the building into rooms [29].

CHAPTER 4

WIND ENGINEERING

4.1 History of wind engineering

Baker [31] divided the European history of wind engineering into five provisional time periods: the "traditional" period (before 1750), the "empirical" period (1750- 1900), the "establishment" period (1900- 1960), the period of growth (1960- 1980), and the modern period (after 1980). The Greek philosopher Aristotle was the first to treat wind as a scientific subject in 350 BC. His treatise Meteorologica is the oldest comprehensive text on meteorology. For nearly 2000 years, this treatise endured as the standard reference in Europe [32]. Aristotle's apprentice, Theophrastus, proposed that wind can be predicted based on the human body and the behavior of animals:

"A dog rolling on the ground is a sign of a violent wind… If the feet swell there will be a change to a south wind. This also sometimes indicates a hurricane."

Sir Isaac Newton published his Principia in 1687, revealing his discovery that the wind force on a given shape is directly proportional to the area of the shape, the air density, and the wind velocity squared [32]. According to Chanetz [33], Newton provided a method which can be expressed as:

"The forces exerted on a solid immersed in a fluid and the fluid are the same either the solid moves with a certain speed through the fluid at rest, or the fluid moves, with the same relative velocity to the solid that it is immobile."

John Smeaton, who is often considered as the "father of civil engineering", proposed a classification of wind forces in 1759 [32]. Professor Alan G. Davenport (1932-2009), the "father of modern wind engineering", proposed in 1961 the concept of the wind loading chain (Fig. 2.3) which provide a conceptual framework to the study of wind loads on buildings and other structures [13]. Cermak [34] defined wind engineering as:

"The rational treatment of interactions between wind in the atmospheric boundary layer and man and his works on the surface of Earth".

4.2 Building codes, standards and national annex

"if a builder build a house for someone, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death."

- Hammurabi's Code of Laws (ca. 1780 BC) [35].

Building codes and standards serves to preserve health, safety and welfare of the public. A code defines what one need to do in the building process, and the standard is a "standard practice" specified within the code [35]. There are numerous of different codes and standards all over the world. For example, Norway follow NS-EN 1991-1-4:2005 (the Eurocode), USA follows ASCE/SEI 7-10 and India follows IS:875-3 [36].

These codes varies. For instance, the calculations in ASCE/SEI 7-10 is based on a three-second gust, compared to Eurocode who is assembled using wind speed average of 10 minutes [36].

Since the nature of wind is different for different regions of the world, national annexes are made. These provides additional information about local wind, terrain, orography etc. However, the calculations described in the codes often tends to overestimate design wind loads, which influence the overall construction cost. Hence, wind tunnel testing and CFD is quite helpful to reduce the likelihood of such overestimations [36].

4.3 History of wind tunnel

In the late 1800s, wind tunnels were a pioneering technology in aerospace engineering. Developed for testing the wind effect on airplanes and airships models. The very first wind tunnel was made in 1871 (Fig. 4.1). Its purpose was to enable studies of the effect of airflow patterns around airplanes. It was an enclosed tunnel, designed by the British marine engineer Francis H. Wenham and built by the British optician John Browning. Wenham's wind tunnel testing led to better understanding of high aspect ratio wings, regarding lift and drag for airplanes [37].

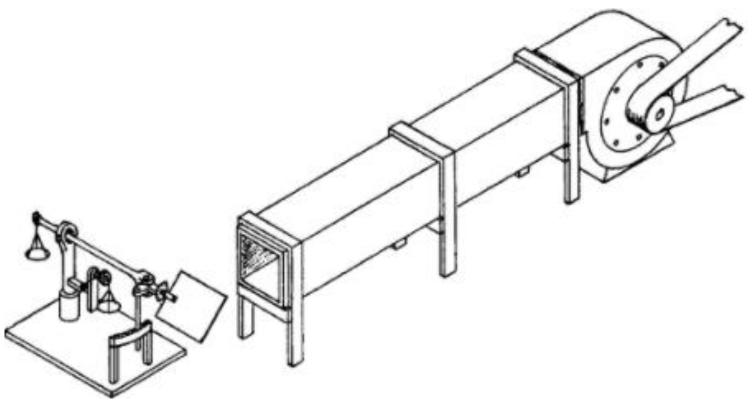


Figure 4.1: Premise sketch of the first ever wind tunnel. Based on Wenham's work of 1871 [37].

During the last 100 years, there has been a huge development in the field of wind tunnel engineering. A wide variety of different types have been constructed, to assist in producing the most aerodynamic design within many different fields. This includes for example design of buildings, bridges, cars, and sporting equipment.

The world's largest wind tunnel (Fig. 4.2) is located at NASA Ames Research Center in California. This gigantic wind tunnel is 427 meters long, and 55 meters wide [38, 39].

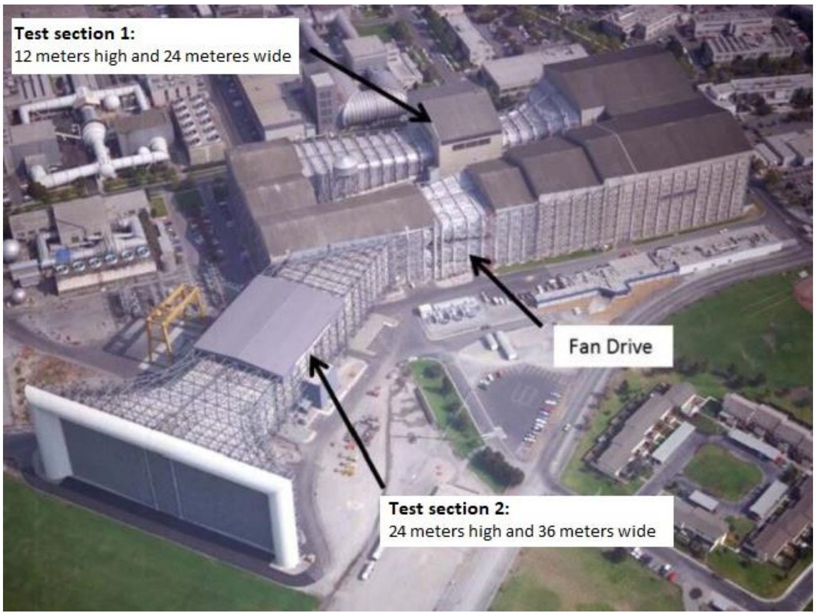


Figure 4.2: Overview of the world largest wind tunnel at NASA. Showing location of test sections and location of fans. It consists of two sections for testing. The wind tunnel is large enough to do full scale test on aircrafts (Photo courtesy of NASA AMES).

4.4 Wind tunnel definition

A wind tunnel is a construction with either closed- or open circuit, usually equipped with large powerful fans to generate wind. Their purpose is to enable studies of the wind effect on anchored objects, such as buildings (Fig. 4.3) or moving objects such as aircrafts (Fig. 4.4) [38].

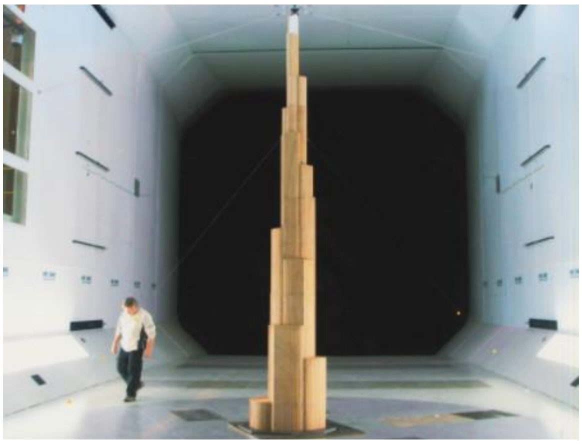


Figure 4.3: Wind tunnel testing of a model of Burj Khalifa (Photo courtesy of RWDI Consulting Engineers).

Figure 4.4 Inside the world largest wind tunnel at NASA Ames Research Center in California. Photo showing test rig for rotor blade (Photo courtesy of NASA Ames Research Center).

4.5 Open return wind tunnel

The two most common types of wind tunnels are open return and closed circuit wind tunnel. An open return wind tunnel (Fig. 4.5) is equipped with one or multiple fans that drags the wind in and over the object placed in the tunnel. The benefit of open return tunnel is that it is: cheap to construct, takes little space and allow use of smoke to study aerodynamic behavior. The downside is “poor” wind flow characteristic when compared to the closed circuit wind tunnel. This is due to curving of the wind as it enters the bell mouth (inlet). It can also be quite noisy due to the big outlet section [40].

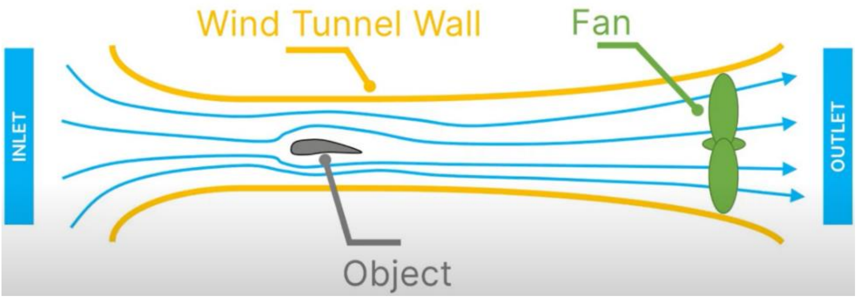


Figure 4.5: Conceptual drawing of open return wind tunnel (Courtesy of airshaper.com).

4.6 Closed circuit wind tunnel

The closed circuit wind tunnel (Fig. 4.6). Fan(s) drives the wind forward. First it interacts with turning vanes, mounted in each corner of the tunnel. This vanes helps to reduce pressure fall and align the flow of the wind. The wind then passes through a honeycomb structure that forces it to move parallel, before interacting with a set of screens. The screens help to break up eddies and to even out the flow pressure. Leading up to the test section there are a big contraction that helps to boost the velocity (Venturi effect) as well as improving the flow quality. After exiting the test section, the wind gets slowed down by the diffuser which have the opposite effect of the contraction.

The benefit of closed circuit tunnel is that it allows for better flow characteristic as to the open circuit tunnel. It also operates quieter. The downside is: higher cost related to construction and heating of the air due to constant circulation [40].

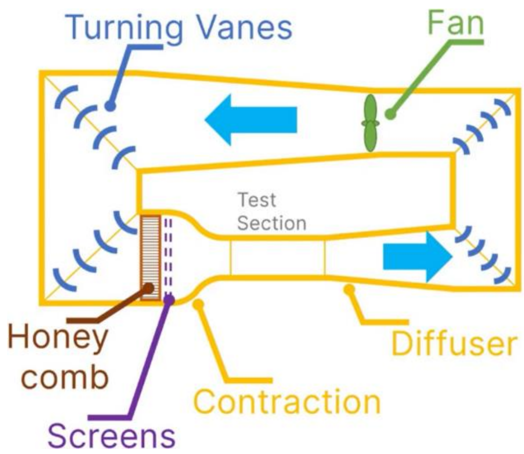


Figure 4.6: Conceptual drawing of closed circuit wind tunnel (Courtesy of airshaper.com).

4.7 Wind tunnel testing

Wind tunnel testing should be done in scenarios like these: building is taller than 120 meters, building has complex geometry, building located in complex terrain, building in interference by existing or future buildings, natural period is greater than 5 seconds, building is very slender [5, 41].

Some of the most used methods for wind tunnel testing are the High-frequency Base Balance method (HFBB) and the High-frequency Pressure Integration method (HFPI). When performing HFBB the model is fixed on a strain gage, which registers overturning/base moment, torsional moment, shear forces and acceleration of the building (Fig 4.7). The base moment results are used as an approach to the design wind load. This method is fast to conduct and inexpensive, but is limited to mostly regular shaped buildings. The HFPI method uses numerous pressure taps that are mounted throughout the building model (Fig 4.8). This method provides more accurate results related to torsional load, shear forces and overall distribution of wind load. However, this method is not favorable for slender models, as it limits available space for mounting of pressure taps [42, 43, 44, 45].

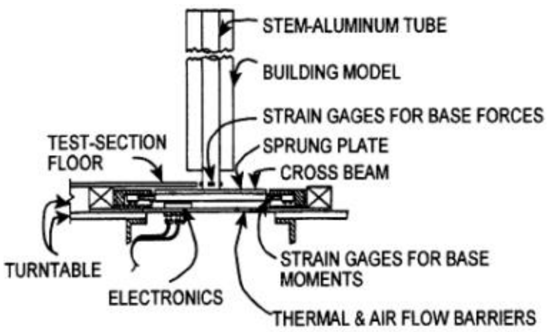


Figure 4.7: Illustration of the HFBB method [44].

Figure 4.8: Building model setup with pressure taps for conducting the HFPI method [45].

Common steps involved during wind tunnel test [42]:

1. Find mean wind velocity, turbulence flow profiles and environmental conditions surrounding the construction site by doing simulations in the tunnel.
2. Make a scaled model of the building, usually between 1:200 to 1:500. Place it in the wind tunnel and examine flow patterns.
3. Gather original dynamic characteristics from structural engineer.
4. Assign desired design wind speeds to the wind tunnel.
5. Collect wind load results.
6. Discuss results with structural engineer to improve structural behavior.

4.8 Computational wind engineering

Computational Wind Engineering (CWE) has throughout the last 50 years become a well-established scientific field in Environmental and Structural Wind Engineering. This is due to advances in computational power and increased accessibility of Computational Fluid Dynamics (CFD) modelling [46].

4.8.1 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) modelling applies numerical methods, by applying computers to solve mathematical equations, to simulate and describe the flows of fluids. This makes CFD highly useful for engineers to predict the behavior of wind, fire development, smoke movement, heat generation, radiation, ventilation flows, etc. CWE is mainly considered as the application of CFD applied for wind engineering purposes. However, in a broader sense, CWE also comprises of other methods of computer modelling. This include wind tunnel and field tests yielding data contributing to the development of CWE models [46]. The significance of the word CFD may vary from different scientific fields applying CFD modelling. Sir Cyril Hinshelwood stated [32]:

"In the 19th century fluid dynamicists were divided into hydraulic engineers who observed things that could not be explained, and mathematicians who explained things that could not be observed."

In the thesis herein, the definition of CWE will be restricted to the application of CFD. Moreover, CFD will be restricted to the application of numerical evaluation in a wind engineering aspect.

There are several methods to perform numerical evaluation of wind loads on buildings. Commonly used methods include: Turbulence modeling, inflow boundary conditions, ground surface roughness, near wall treatments, and quantification of wind loads.

There exist several guidelines for the application of CFD modelling. According to Franke & Baklanov [47], the best practice guidelines for CFD modeling of the flow in urban environment are applying statistically steady RANS equations for neutrally stratified flow field. When applying CFD simulation, several decisions must be made by the engineer regarding various parameters. The general steps [47, 48] for conducting a numerical simulation are:

- Deciding on what mathematical equations to use to describe the wind flow. Some of the most widely used methods are URANS, steady RANS, LES, and hybrid URANS/LES.
- How detailed the building models should be in their geometry and overall appearance.
- The size of the area that is to be modelled. This is referred to as the computational domain (Fig. 4.9). This might be a wall, a part of a structure, a building, a building with surrounding area with or without neighboring structures, etc.
- The computational mesh/grid. The computational domain consists of a vast number of mesh cells. By applying computational tools, calculations are carried out for every single cell, providing a final solution regarding the simulated flow.
- The boundary conditions defining the inputs of the model. Examples of conditions are wind speed, volumetric flow rate, and wind angle of attack.
- Discretization methods are used to divide the solution of a system of differential equations into a discrete function. The solution values represent points forming the mesh. The discretization schemes make up the spacing between each point in this mesh [49].
- The initial flow conditions must be defined. These represent flows present within the domain prior to simulation. Choosing representative data inputs can be a challenge, especially if turbulence is present. Thus, one may need to run simulations to obtain the initial conditions, before doing the main simulation.
- Appropriate time step must be chosen. Often some fraction of the characteristic velocity over some characteristic length is used. Smaller time steps will lead to definite convergence but is much more time consuming [47].
- Applying the iterative convergence criteria. Most CFD software use iterative methods for solving algebraic systems of equations involved. By initially guessing, the flow variables are recalculated in every iteration until solutions are obtained.

Studies [47, 48] have shown that these parameters play an important role in analyses and may highly impact the results. Coleman & Stern [50] divided the sources of errors and uncertainties into: (1) Errors and uncertainties in modelling the physics. These result from the assumptions and approximations used in the equations. (2) Numerical errors and uncertainties. These originate from the numerical solution of the mathematical model [47].

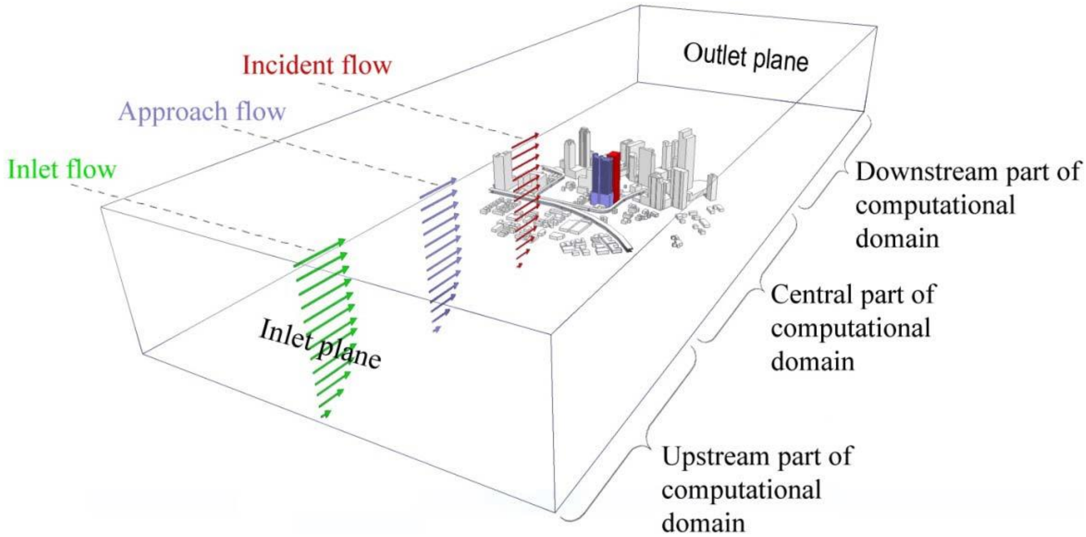


Figure 4.9: Example of a computational domain for CFD with building models in central part (modified by [51] from [52]).

CHAPTER 5

METHODS TO REDUCE WIND RESPONSE

5.1 Structural methods

The two most common strategies to mitigate wind actions are described herein:

5.1.1 Increasing structural rigidity

The simplest method to reduce lateral loads caused by wind is to make the structure more rigid. Increasing rigidity for tall buildings is related to huge costs regarding materials, such as steel and concrete. In most cases this method is only sustainable for low-rise buildings.

Thus, in the 1960s, civil engineer Fazlur Rahman Khan invented a new method to increase rigidity for tall buildings. This method was called “system of framed tubes”, consisting of triangular tubes to allow for more sufficient transfer of wind loads from the exterior structure (tube system) to the interior structure (columns).

John Hancock center (Fig. 5.1) in Chicago used this method, enhancing rigidity and at the same time reducing use of steel. This led to a highly rigid structure, more useable floor space and cost reduction of approximately 50 % related to steel. Today, this method is commonly used for buildings exciding 150 meters to reduce lateral loadings [37].

Figure 5.1: John Hancock Center in Chicago, built using the system of framed tubes. The Diagonal bracing is continuous for all faces of the building. The bracing is connected to the columns, forcing loads to transfer from exterior structure to the interior columns (Photo courtesy of Antoine Taveneaux) [37].

5.1.2 Dampers

Dampers could be compared with a shock absorber, like the ones we find in cars for instance. Both systems have the same job, which is to dissipate the kinetic energy, providing comfort for the occupant and adding structural integrity.

"Damping is the degree of energy dissipation that a structure can provide to reduce buildup of the resonant response" - Alaghmandan & Elnimeiri [53].

Damping is branched into two systems, active and passive. Where active system can be active mass dampers (AMD) and active variable devices (AVSD). Viscous dampers (VD) and tuned mass dampers (TMD) (Fig. 5.2) are some of the passive systems that exists [53].

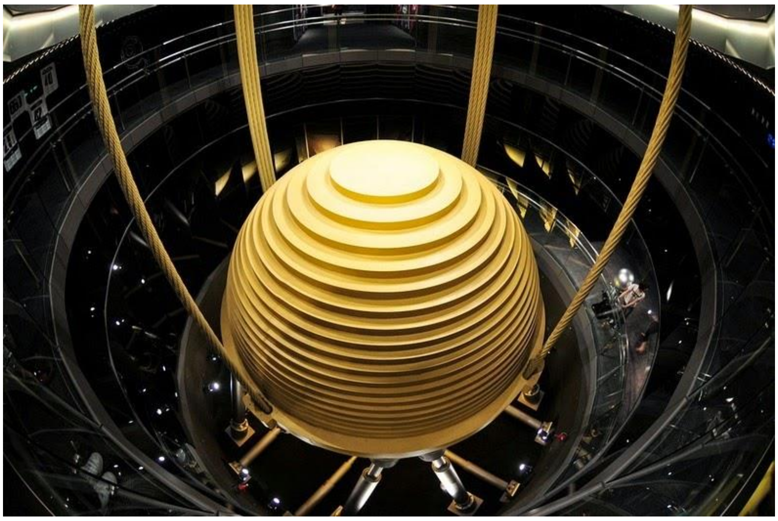


Figure 5.2: TMD inside Taipei 101 (Photo courtesy of flickr.com). The ball *(mass)* is roughly 5.5 meters in diameter, weighs approximately 6.6 x 10^5 kg, and is suspended by 92 steel cables, each cable 42 meters long with diameter of 8.9 cm. It is also subjected to eight hydraulic dampers that helps to consume the kinetic energy the wind performs on the building (Photo courtesy of flickr.com) [54].

5.2 Architectural methods

Changing the architectural design from traditional regular shape to irregular shape allows buildings to be more aerodynamic in the face of wind.

"Aerodynamic forms act like an unexpected form in a relationship with wind and can reduce the along wind response as well as across-wind effect by confusing the wind."

- Alaghmandan & Elnimeiri [53].

Some of the architectural methods that are used to mitigate the wind effect is describe in section: 5.2.1-5.2.5

5.2.1 Tapering

Tapering means to build progressively slimmer towards the top (Fig. 5.3). This allows for reduction in the across-wind effect, as well as some reduction in the along-wind. Building slimmer towards the top also reduces the trappings of vortex shedding, when compared to regular building [53].

Figure 5.3: The shard in London. Built using the tapering method, influenced by spires of London churches and masts of tall ships from the 1800s. The shard is London's tallest building, 310 meters high consisting of 95 story's (Photo courtesy of Getty Images) [55].

5.2.2 Setback

Setback is based on the tapering method combined with sculpting. This method serves almost same effect regarding the across-wind as tapering does but have some challenges when it comes to trapping of vortex shedding in regions of setbacks [53, 56].

Figure 5.4: Burj Khalifa, located in Dubai is the World`s tallest building (828 meters). Built as a Y-shaped structure with setbacks (Photo courtesy of tourist-destinations.net) [57].

5.2.3 Openings

By creating openings (Fig. 5.5) in the structure as it rises, the induced wind area will be reduced, leading to less effects regarding dynamic wind response (i.e. openings will decrease the overall wind effect on the building) [53].

Figure 5.5: Kingdom Centre in Saudi Arabia. The Building is 302 meters heigh and is connected at the top by a 56 meters bridge with public observation deck, allowing for view over the capital, Riyadh (Photo courtesy of kiwicollection.com) [58].

5.2.4 Twisting

Building the structure with twisting as it rises creates an aerodynamic response that reduce vortex shedding. Twisting is also seen practical in reduction of the across-wind [53].

Council on Tall Buildings and Urban Habitat (CTBUH) [59] defines twisting buildings as:

"one that progressively rotates its floor plates or its façade as it gains height."

The design team and engineers behind Shanghai tower (Fig. 5.6) ran multiple wind tests before they landed on a twisting design of 120 degree. This design led to a remarkable 24% reduction in wind loads compared to a regular shaped building of same height. Which allowed for a lighter structure resulting in saving approximately 58 million dollars related to materials [60].

Figure 5.6: Shanghai Tower. World's second tallest building at 632 meters, and the tallest in China (Photo courtesy of Tansri Muliani).

5.2.5 Corner modification

Several corner modifications can be done to buildings, for example corner chamfered (softening), rounding and corner cutouts. Modifications like these can help to reduce across-wind up to 40%, and along wind up to 30% in comparison of a regular building [53]. Irwin [61] states that, to gain most beneficial effect the: *".. softening should extend about 10% of the building width in from the corner".*

Engineers behind Taipei 101 (Fig. 5.7) used corner modifications to redirect and "confuse" the wind. Wind tunnel testing of Taipei 101 displayed 25% decrease in the base moment, compared with a regular shaped building [61].

However, some studies have showed that corner modification can result in worse aerodynamic behavior when compared to regular shape buildings [53].

Figure 5.7: Taipei 101 is 508 meters, consisting of 101 stories. Located in Taipei, Taiwan. This is the tenth tallest building in the world (photo courtesy of Luca Vittorio Calvetti) [62].

CHAPTER 6

WIND IN URBAN ENVIRONMENT

6.1 Wind effect of tall buildings in urban habitat

In urban cities tall buildings greatly affects patterns and the velocity of the wind at street level (Fig 6.1). Hence, it is important to analyze these effects using CFD and wind tunnel experiments before starting construction. This to ensure comfort and safety for pedestrians, cars and other activities going on in the streets [63].

Figure 6.1: Street in Toronto, 1986. Here, wind due to buildings became so strong that they had to install ropes in the streets, which pedestrians had to use to get around (Photo courtesy of CBC).

Some of the most commonly challenges related to wind environment at street level associated with tall buildings in densely built cities are described here in:

6.2 Downdraught effect

When wind hits a heigh-rise building a good portion of the wind is reflected down, into the streets. This is referred to as the downdraught/downwashing effect (Fig 6.2). The downdraught effect increases with the height and width of the building, and is larger for buildings with poor aerodynamic design, e.g. rectangular shaped buildings [64].

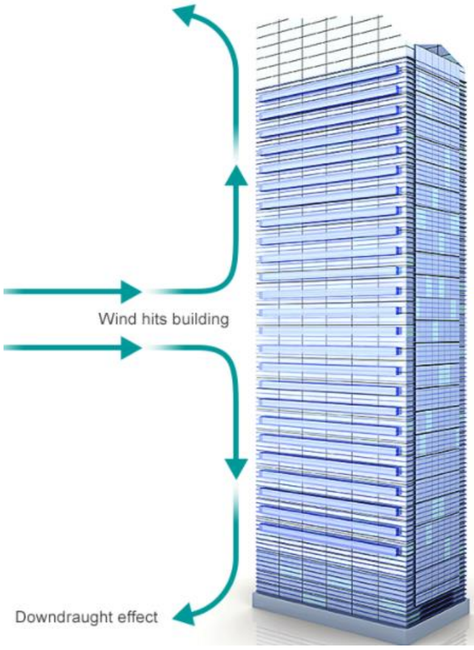


Figure 6.2: The downdraught effect (Photo courtesy of BBC).

6.3 Street canyons

When buildings are located near each other, “street canyons” (venturi effect) occurs (Fig 6.3). The street canyon phenomena creates strong winds and is not only a problem for pedestrians. It will also induce larger wind loads on buildings if they are built were street canyons occurs (exemplified by the blue box on Figure 6.3). Hence, the importance of wind tunnel and CFD simulations for urban cities [64,65].

Figure 6.3: Yellow arrows indicating wind flow coming from separate streets. Here, the wind has “low” velocity and high pressure. When the wind meets like indicated by the red arrow, the pressure drops, forcing the velocity of the wind to increase extensively (Photo courtesy of CBC).

6.4 Methods to reduce downdraught and street canyons

This section is limited to some of the most frequent used methods to improve wind environment at street level.

6.4.1 Reduce downdraught

By using the tapered building method (Fig 5.3), downdraught effect will be reduced when compared to a rectangular building of the same height. This is due to less width as the building grows. Thus, the interaction area becomes smaller as tapered buildings increase in height, which results in less air being forced down towards the streets.

6.4.2 Reduce street canyons

To reduce street canyons the spacing between buildings are the main factor, as well as the street morphology and height of the buildings [63].

6.4.3 Adding vegetation and sculptures

In areas where buildings already exist, adding vegetation such as trees and shrubbery is a good way to reduce both mentioned cases. Sculptures, fences, podiums, canopies (Fig 6.4), etc. could also be added to reduce these types of wind effects [65, 66].

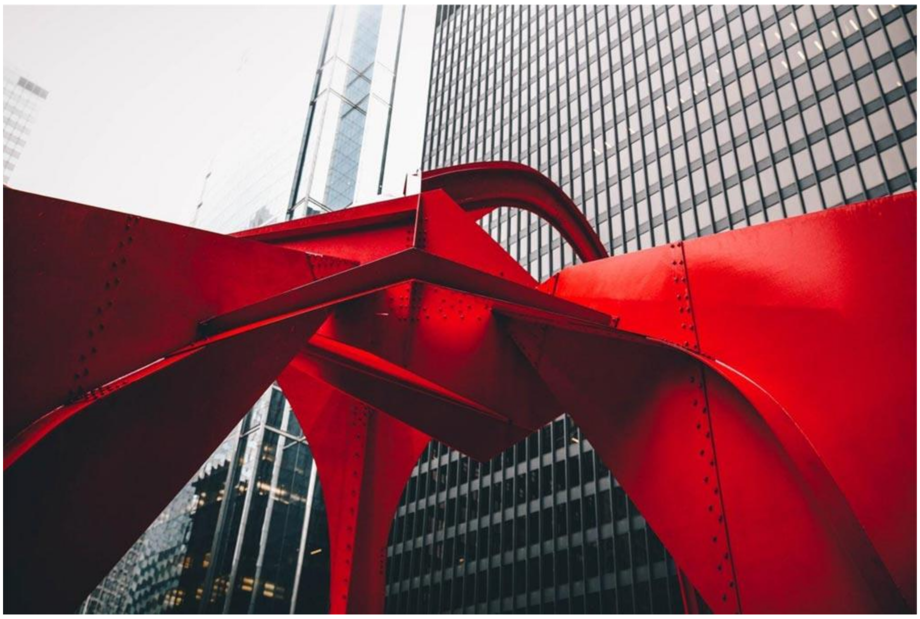


Figure 6.4: Canopy outside The Leadenhall building in London. Downdraught effect caused by Leadenhall forced one to place this canopy outside to reduce downdraught at street level (photo courtesy of windtechconcult.com) [66].

CHAPTER 7
PRESSURE COEFFICIENT STUDIES

This chapter looks at previous studies that mainly focus on pressure coefficient for irregular shaped tall buildings.

7.1 E–shaped building

Bhattacharyya *et al.* [67] conducted tests on an E-shaped building (Fig 7.1) using experimental wind tunnel setup (Fig 7.3) at the Institute of Technology Roorkee, India. Analytical study was also performed using CFD method in combination with ANSYS CFX software. The tests were carried out using application of wind load in the boundaries 0° until 180° with intervals of 30° (Fig 7.2). Terrain, equal to category II in NS-EN 1991-1-4:2005 was simulated placing square cubes of distinct shapes in the wind tunnel combined with a vortex generator.

Ahead of testing the wind velocity was adjusted to 10 m/s for the wind tunnel, using 10% turbulence intensity. Results showed maximum positive C_p of 0.8 for face E, at an inclination of 180° and maximum negative C_p of -0.68 for face A, with inclination 90°. (Table 7.1). It also concluded that maximum positive C_p for face K (0°) compared to maximum negative C_p for face E (180°) had almost same standard deviation due to wind load hitting perpendicular on both faces. (Fig 7.4). The study also concluded that the experimental and analytical work where within the adequate limits and could be incorporated in relevant codes for wind calculations [67].

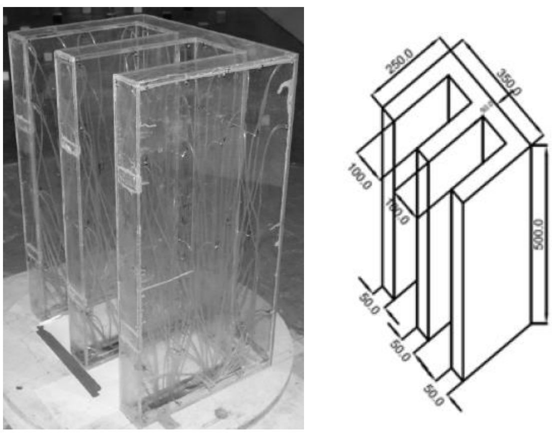


Figure 7.1: Model of E-shaped building used in wind tunnel testing, scale 1:300 (left). Isometric drawing of E-shaped building (right) [67].

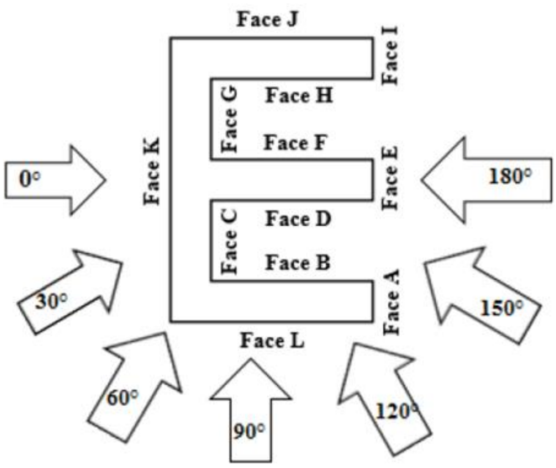


Figure 7.2 Wind test angles used during testing of E plan shaped building [67].

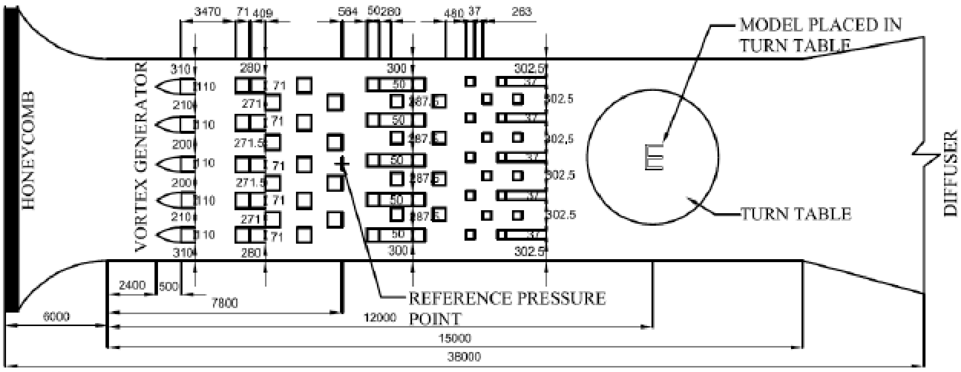


Figure 7.3: E-shaped building model connected to 210 pressure tapping points, placed on turn table inside wind tunnel. Turn table is used to turn the model to test different wind inclinations [67].

Table 7.1: C_{p} - values for all wind angels on E-shaped building [67].

Face	Angle of Wind Flow						
	0°	30°	60°	90°	120°	150°	180°
A	-0.38	-0.28	-0.26	-0.68	-0.1	0.62	0.39
B	-0.34	-0.29	-0.28	-0.67	-0.01	0.43	0.47
C	-0.31	-0.25	-0.26	-0.61	0.13	0.51	0.55
D	-0.33	-0.25	-0.25	-0.67	0.13	0.51	0.53
E	-0.28	-0.22	-0.28	-0.47	0.08	0.51	0.8
F	-0.33	-0.22	-0.27	-0.36	-0.13	0.31	0.53
G	-0.31	-0.3	-0.28	-0.38	0.04	0.39	0.55
H	-0.34	-0.34	-0.41	-0.37	0.07	0.41	0.47
I	-0.38	-0.27	-0.46	-0.24	-0.15	0.23	0.39
J	-0.51	-0.32	-0.27	-0.21	-0.33	-0.33	-0.57
K	0.55	0.48	0.03	-0.49	-0.38	-0.26	-0.3
L	-0.51	0.01	0.36	0.44	0.45	0.11	-0.57

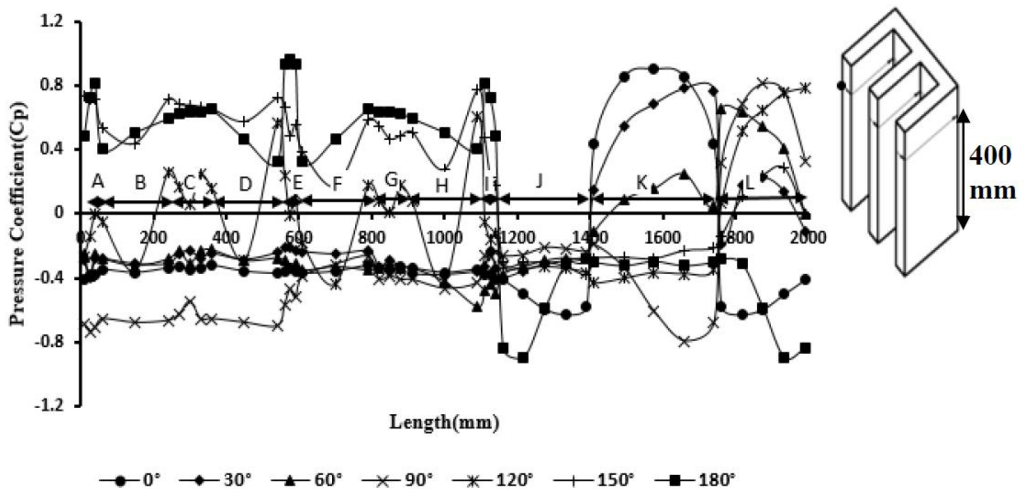


Figure 7.4: Variation of Cp - values for angles between 0° - 180° on E-shaped building. Values oscillates from negative to positive with essentially same intensity from face A to I. Standard deviation for 0° & 180° is approximately the same [67].

7.2 L- and U-shaped buildings

Gomes *et al.* [68] carried out wind tunnel tests of L and U-shaped buildings, combined with numerical analyses at the National Laboratory for Civil Engineering in Portugal. The experimental tests were executed in a closed return wind tunnel (Fig. 4.6), with a multi-channel pressure measurement system to record wind loads at different angles. CFD (Fig. 4.9) with PHOENICS package was used for the numerical analyses.

A preliminary study of a cube-shaped building (Fig 7.5) with same scale and same boundary conditions as the L- and U-shaped was performed and compared with previous studies to check for correct data input. For the wind tunnel tests, wind velocity was set at roughly 10 m/s with uniform upstream flow. L- and U-shaped building models were placed in the wind tunnel (Fig. 7.6) and subjected to wind at angles ranging from 0° until 180° [68].

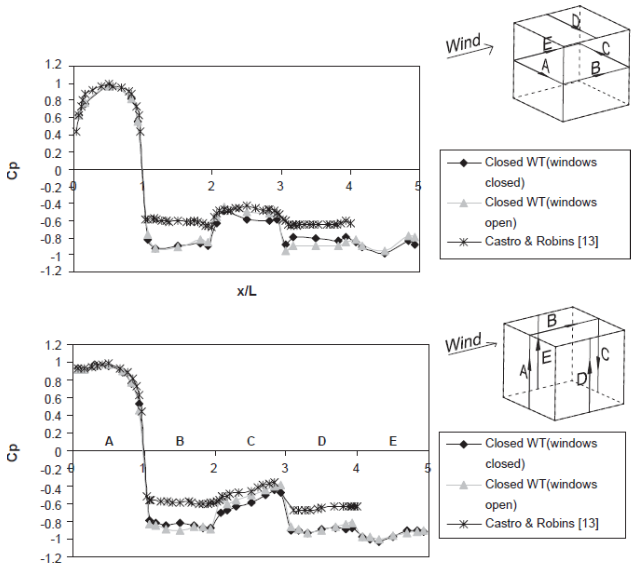


Figure 7.5: Preliminary cube-shape study in comparison with earlier study done by Castro & Robins [69]. Result showed good relationship between pressure coefficients for both studies, indicating correct input data [68].

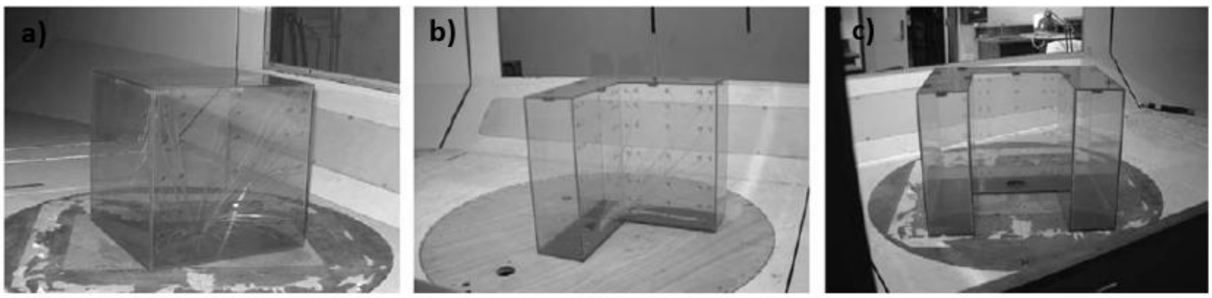


Figure 7.6: a) Cube-shaped building model, used for validation of empirical wind data before testing of L and U-shape. **b)** L-shaped building model inside wind tunnel **c)** U-shaped building inside wind tunnel. All models are in 1:100 scale [68].

The study showed mostly good compliance between numerical- and experimental results. Maximum positive C_p for L-shaped was approximately 1.0, for induced wind angle of 45° (Fig. 7.7). The maximum negative C_p was registered at angle 180°, yielding a value of – 0.65 (Fig. 7.8). At 0° for U-shaped, the maximum positive C_p was in the region of 0.90 (Fig. 7.9) and maximum negative C_p close to -0.80 for 180° (Fig. 7.10).

Some overestimation errors occurred in the numerical study. However, the overall result was noted withing acceptable boundaries, providing valuable data regarding pressure coefficients for these types of irregular-shaped buildings [68].

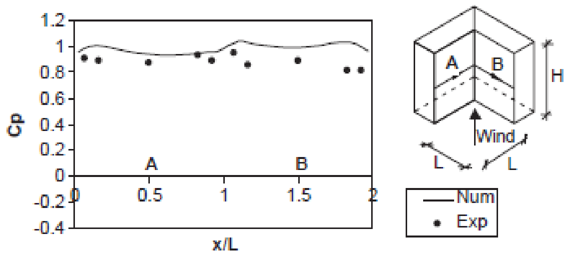


Figure 7.7: C_p – values from numerical analysis (Num) and experimental data (Exp). Maximum positive C_p at 45° [68].

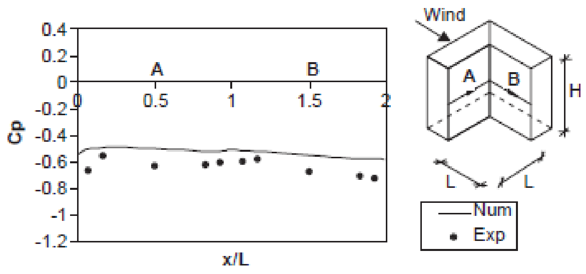


Figure 7.8: C_p – values from numerical analysis (Num) and experimental data (Exp). Maximum negative C_p at 180° [68].

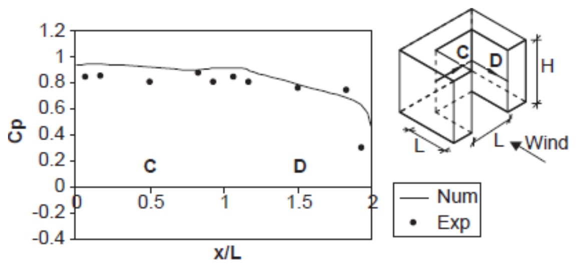


Figure 7.9: C_p – values from numerical analysis (Num) and experimental data (Exp) for U-shape. Maximum positive C_p at 0° [68].

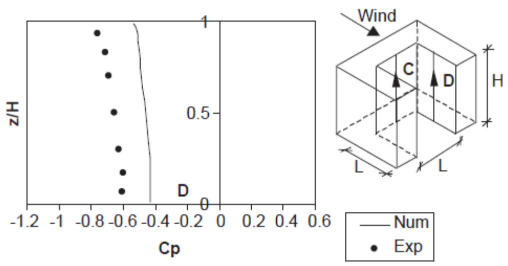


Figure 7.10: C_p – values from numerical analysis (Num) and experimental data (Exp) for U-shape. Maximum negative C_p at 180° [68].

7.3 Various irregular shaped buildings

Tanaka *et al.* [70] conducted wind tunnel testing in a closed return tunnel (Fig. 4.6) combined with CFD (Fig 4.9), for 33 models of various irregular shape. This to examine the difference in wind pressure and aerodynamic response due to changes in geometry. Models with corner recession, setback, tapering, helical-shape, and through openings were tested, some combined with different twist and angles (Fig 7.11).

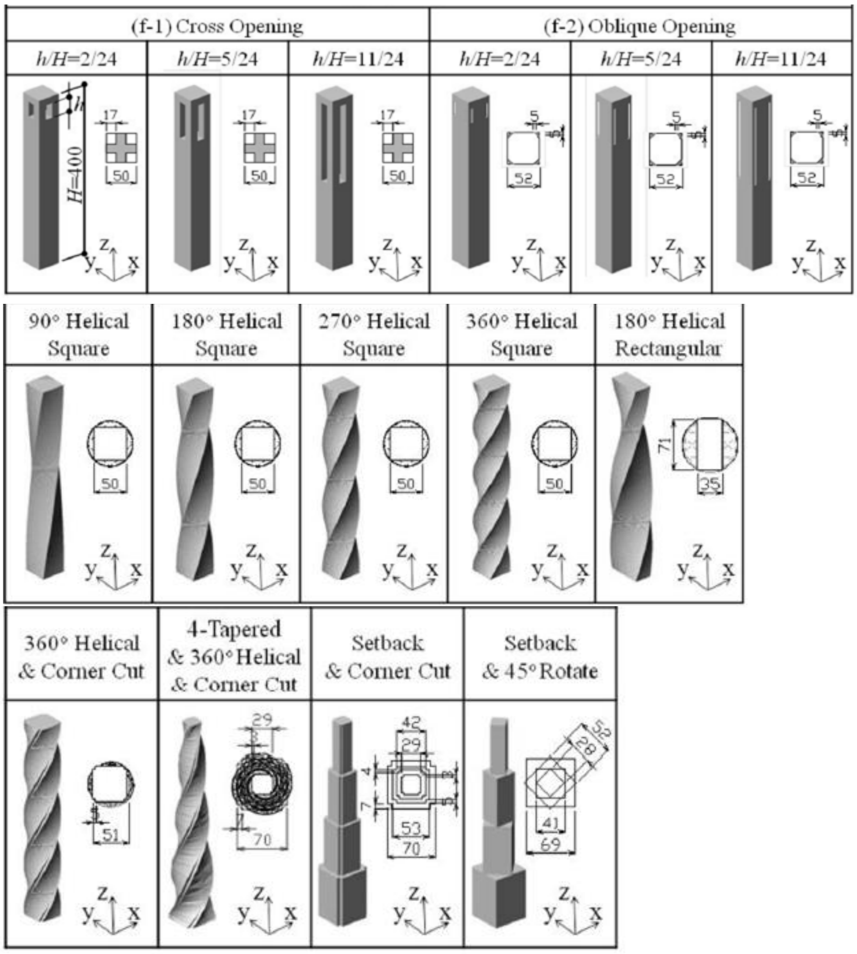


Figure 7.11: 15 of 33 models that were tested in the wind tunnel testing [70].

The models were tested using turbulent flow boundary layer, corresponding to terrain category IV in NS-EN 1991-1-4:2005. HFFB method (see chapter 4.4) were used.

Four models: Square, Corner Cut, Setback and 180° Helical with single modifications were later compared to make a summary of the difference in wind loads and vortex shedding due to their inequality in geometry. Throughout the test, the design wind speed was adjusted from 30 m/s until 71 m/s, using intervals of 1 m/s. (Wind speed of 71 m/s is equivalent to a 500 year-return-period).

Results from wind tunnel testing and CFD simulations revealed a significantly lower degree of design wind load for the 180° helical model. The decrease was 30% compared to the square model. The results also uncovered that the 180° helical model and the setback model were less subjected to along-wind and across-wind excitations.

Degree of vortex shedding was significantly higher for the square model than for the others (Fig 7.12). Due to low degree of across wind and vortex shedding the helical 180° model also performed best regarding comfort and safety for the occupants. Pressure coefficient, C_p, were also simulated, revealing that square model had the greatest pressure coefficient (Fig 7.13).

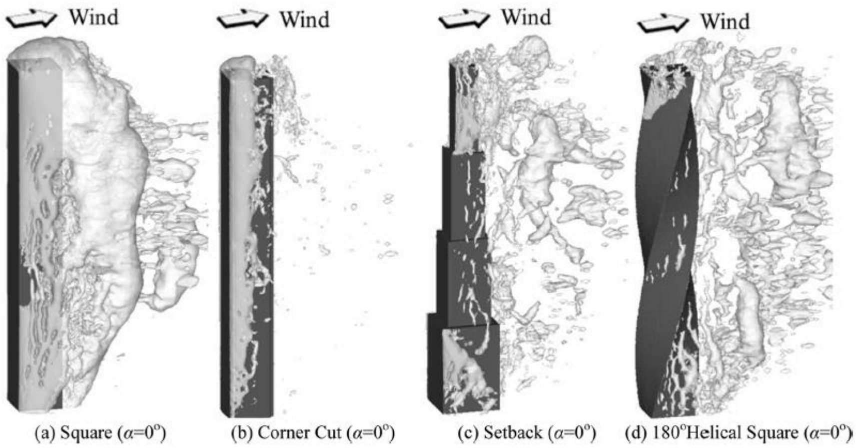


Figure 7.12: Flow patterns and indication of regions of vortex shedding [70].

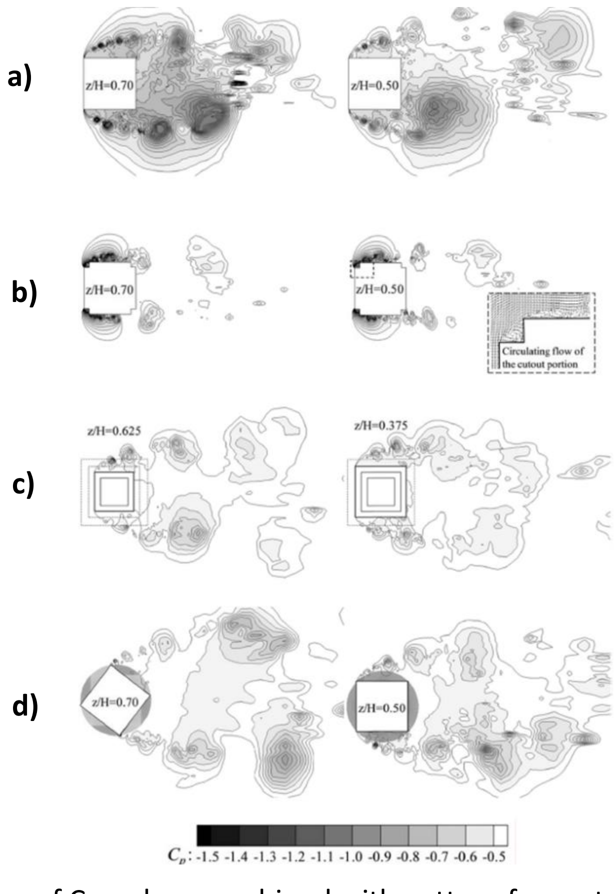


Figure 7.13: Contours of C_p -values combined with pattern for vortex shedding: **(a)** square **(b)** corner cut **(c)** setback **(d)** 180° helical [70].

7.4 Hexagonal shaped buildings with modifications

Thamanna & Krishnachandran [72] analyzed the wind flow patterns around hexagonal shaped tall buildings with different aerodynamic modifications (Fig. 7.14). By comparing with a basic hexagonal shaped model without modifications, the study found that modifications to the building give better wind response. This can be observed from the reduced pressure coefficients (Table 7.3).

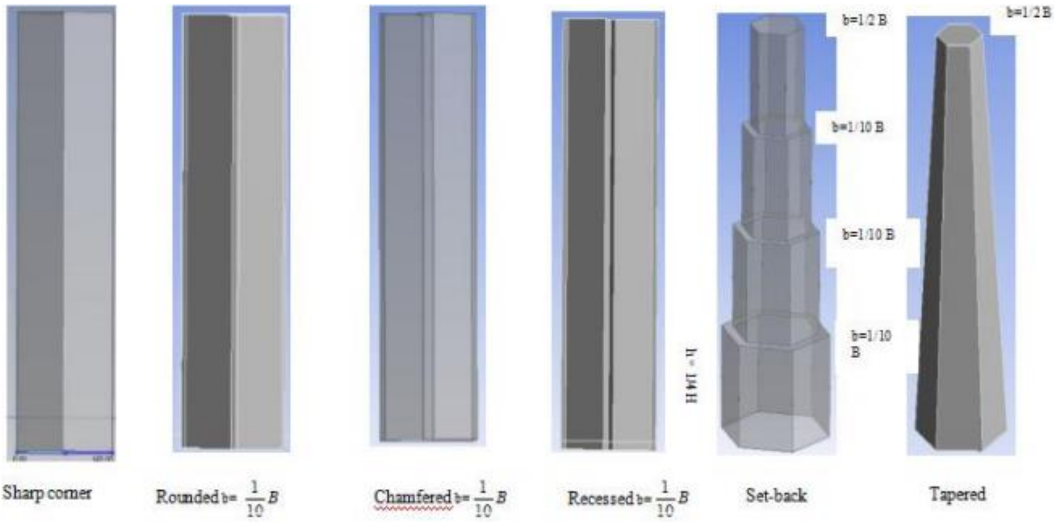


Figure 7.14: Hexagonal models with various modifications [72].

Table 7.2: The average pressure coefficients on each side of the different models tested. Included is the measured C_p reduction (in %) resulting from aerodynamic modifications [72].

Model	Pressure coefficient Cp of different faces											
	A	% redu ction	B	% redu ction	C	% reduct ion	D	% reducti on	E	%reducti on	F	% redu ctio m
Basic	1.3	-	-1.133	-	-1.133	-	-1.196	-	-1.193	-	-0.795	-
Rounded	0.624	52	-0.861	24	-0.861	24	-0.917	23.32	-0.917	23.1	-0.712	10.4
Chamfered	0.855	34.2	-1.049	7.41	-1.046	7.41	-1.06	11.1	-1.06	11.1	-0.737	7.29
Recessed	0.598	54	-0.669	40.9	-0.669	40.9	-0.889	25.6	-0.887	25.6	-0.616	22.5
Setback	1.081	16.8	-0.517	54.3	-0.517	54.3	-0.997	16.6	-0.997	16.43	-0.694	12.7
tapered	1.007	22.5	-0.573	49.4	-0.579	49.4	-1.04	13.04	-1.095	8.21	-0.504	36.6

The pressure coefficients show that there will be suction on every side of the building, except on the side perpendicular to the angle of wind attack (side A). The areas subjected to low degree of negative wind pressure, are experiencing "wake", which results in drag forces on the leeward sides. The analysis showed that the recessed model (Fig. 7.15d) will have the best performance of the tested models. In the case of the basic hexagonal model, symmetrical vortices are created on the leeward side of the building model (Fig. 7.15a). For the recessed corner model, smaller degree of vortex shedding is observed, and the air flow appears to be less chaotic (Fig. 7.15d). For the remaining models, the formations of vortex shedding appear to be interrupted and thus less impactful compared to the basic model [72].

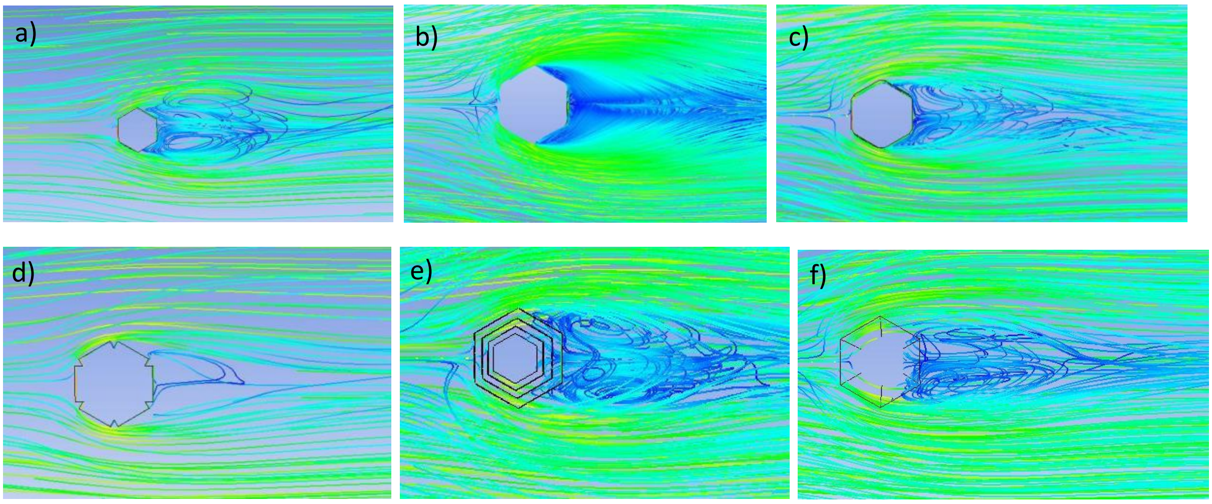


Figure 7.15: Simulated wind flow around the different hexagonal building models: **a)** Basic hexagonal shaped model. **b)** Hexagonal model with rounded corners**. c)** Hexagonal model with chamfered corners. **d)** Hexagonal model with corner recession. **e)** Hexagonal model with set-back [72].

7.5 Octagonal shaped buildings

Verma *et al.* [73] measured the average wind pressure on the sides of a uniform octagonal shaped (Fig. 7.16) tall building at three different wind incident angles (0^o, 15^o and 30^o) using CFD simulation. The study showed that when the wind incidence angle is perpendicular (0^o) to a building side, maximum positive pressure is imposed on this side (Table 7.3). As the wind incidence angle increases on a building side, the positive pressure decreases on this side, and the total degree of suction on the building sides increases. Positive wind pressure increases with increasing height on windward side because wind velocity increases with height. The maximum pressure is present along the vertical center line of the windward side (side A) and decreases towards its edges (Fig. 7.17).

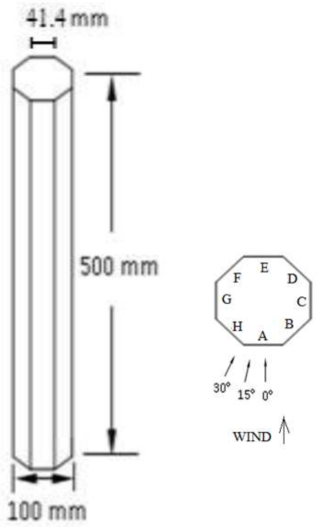


Figure 7.16: Octogonal building model and the three tested incidence angles [73].

Table 7.3: Average C_p values for the different sides of the octagonal shaped building at the three tested angles of incident [73].

Wind Incidence Angle	C_p(mean)value for Building Face							
	Face A	Face B	Face C	Face D	Face E	Face F	Face G	Face H
0°	0.835	0.287	-0.572	-0.694	-0.638	-0.674	-0.572	0.286
15°	0.776	-0.38	-0.58	-0.705	-0.681	-0.668	-0.601	0.34
30°	0.473	-0.447	-0.671	-0.63	-0.634	-0.627	-0.514	0.681
Max +ve	**0.835**	**0.287**	**-0.572**	**-0.63**	**-0.634**	**-0.627**	**-0.514**	**0.681**
Max -ve	**0.473**	**-0.447**	**-0.671**	**-0.705**	**-0.681**	**-0.674**	**-0.601**	**0.286**

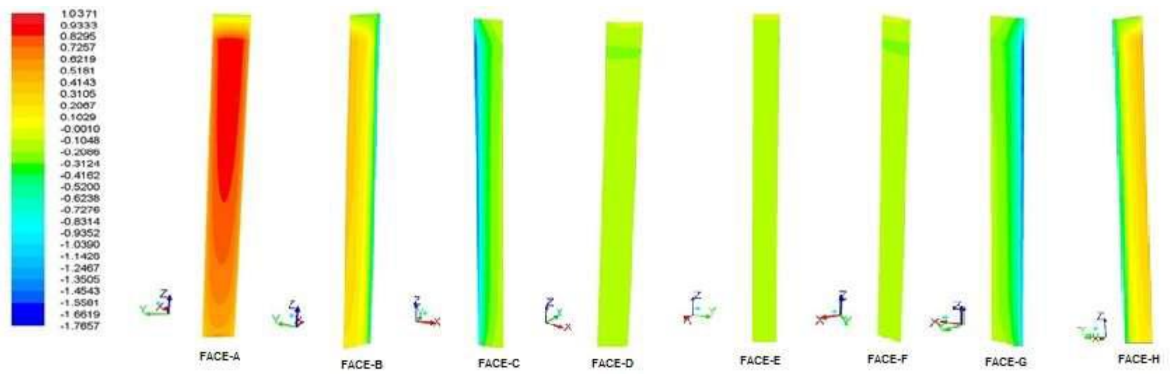


Figure 7.17: Contours of the wind pressure coefficients at 0° , face A of octagonal model [73].

CHAPTER 8

DISCUSSION

During the last few decades, there has been a vast increase of studies investigating the advantages of aerodynamic modifications of tall buildings to reduce wind loads. Such methods have proven highly advantageous in reducing wind responses, because they alter the wind flow patterns around buildings. To enhance the wind performance of tall buildings, structural methods and architectural modifications are the most common strategies.

Structural methods include:

(1) “System of framed tubes” (Fig. 5.1) which is a structural method to enhance rigidity. This method is widely used for steel, reinforced concrete, and composite constructions. This method makes the building behave like a huge vertical cantilever to resist overturning moments [74].

(2) Installing dampers (Fig. 5.2) contributes to dissipate the kinetic energy. Such systems have proven highly advantageous for buildings with over 40 stories and will improve the occupant comfort level significantly [74]. The use of dampers is becoming more and more common.

The architectural methods include:

(1) Tapering (Fig. 5.3) which contributes to reduction of the across-wind effect [68]. Kim & You [75] reviewed the effect of tapering of square shaped buildings. The study showed that tapering will result in a much better wind performance of buildings in across-wind directions. The positive effect of tapering in the along-wind direction was not as significant. To achieve the greatest positive structural effect of tapering, the tapering should extend throughout the full height of the building. By using the tapering method, the wind induced lateral movement of tall buildings is reduced by 10 to 50%. The higher and slenderer the building, the greater the positive effect of tapering will be. Having the slope of tapering be 8%, may result in a 50% reduction in the lateral movement for a 40-story building [74]. Baker & Pawlikowski [56] discussed experiences related to the construction of Burj Khalifa (Fig. 5.4). The method of tapering is easier and faster to construct than the setback, or setback combined with the tapering method. Therefore, the next generation of supertall buildings should be built using only the tapering method [56]. This will reduce construction time, and by that reduce costs.

(2) Setbacks (Fig. 5.4) is another widely used method. Kumar & Kumar [76] showed that the urban environment can be highly improved by using setbacks. A 29% reduction in wind fluctuation speed in front of the building could be obtained by setback modifications. On the leeward side of the building, a 69% reduction in wind fluctuation speed was observed. Even though the setback method can create a greater architectural look than tapering, buildings with setbacks are subject to greater wind loadings caused by vortex shedding [56]. Kim & Kanda [77] studied the effect of setbacks and tapering for tall, square shaped buildings. The

analysis showed that the mean pressure coefficients on windward side of all the models were approximately the same. However, the C_p - values on leeward side varied. The study showed that setback and tapering will result in the formation of vortex shedding higher above the ground than without modifications. Roy & Bairagi [78] showed that a change in the wind incidence angle on a building with setbacks, may drastically change the degree of suction upon the building.

(3) Opening through the building is a very effective method to improve the wind response. To achieve the best effect, this should be constructed near the top of the building (Fig. 5.5) [79]

(4) Twisting of buildings (Fig. 5.6) has become more and more common. This is a relatively new method but has proved to effectively reduce vortex shedding. Multiple wind tests were conducted before the construction of Shanghai Tower (Fig. 5.6). A twisting design of 120^o was finally chosen. This design led to a remarkable 24% reduction in wind loads compared to a regular shaped building of same height. This allowed for a less compact building, resulting in material cost savings of 58 million dollars [60].

(5) Corner modifications, such as corner chamfered, rounding and corner cutouts. Kawai [80] showed how corner modifications will alter the wind induced loads on tall buildings. This was also demonstrated by Dutton & Isyumov [81] and Tamura & Miyagi [82]. Irwin [61] found that corner modification of the Taipei 101 Tower (Fig. 5.7) resulted in a 25% decrease in base moment compared to regular shaped building of same height. Neethi & Joby [79] studied aerodynamic modifications of tall, rectangular buildings. This study showed that for tall, rectangular buildings, rounding of the corners would give the best along-wind performance.

<u>Impact on urban habitat</u>

Tall buildings may impact the urban habitat in negative ways, by altering the pedestrian wind conditions, blocking sun light and by that casting huge shadows, etc. Nevertheless, the future development and the evolution of tall building construction is inevitable. Tall buildings generate acceleration of ground level wind speed. This may influence the urban habitat and make it less comfortable and safe for pedestrians. Neighboring buildings will also affect the wind flow pattern around a particular building and can in some cases increase wind speed (Fig. 6.3) [83]. As more tall buildings are constructed in urban area, the resulting wind flow patterns become more complex and unpredictable. Urban planning regulations and zoning laws aim to regulate the use of land to avoid such problems.

<u>Building geometry and orientation</u>

In addition to geometry, the positioning of tall buildings is a governing factor controlling the building's parametric coefficients and wind response. Amin & Ahuja [84] studied four rectangular buildings with the same base area and height, but various side lengths. Their experimental wind pressure measurements demonstrated the impact of the side-to-width ratio and orientation of the buildings with respect to the incidence angle. When the incidence angle is perpendicular (0^o) to the windward wall, the side-to-width ratio affects the magnitude and distribution of the pressure coefficients to less degree. Hence, positioning the building in the best possible direction will reduce the wind loads imposed on the building. This is a simple and economical method to reduce the imposed wind loads and thereby minimizing construction material costs and optimizing the habitability comfort level.

Square shaped buildings are more economically effective and serviceable, compared to rectangular shaped buildings. However, if the angle of wind attack is perpendicular to the shortest side of a rectangular building, the wind response of the building will be considerably better than in the case of square plan shaped buildings [74]. Merrick & Bitsuamlak [85] found that rectangular, triangular, and elliptical shaped buildings are more susceptible to high torsion loading (Fig. 2.4), than square and circle shaped buildings.

Because of the above-mentioned reasons, the shape and orientation of buildings with respect to the prevailing wind direction should be considered early in the design stage to achieve the best possible wind performance [85, 86, 87, 88].

Building codes

Eurocode and other building codes are not applicable for very tall, irregular shaped buildings. This is because it is impossible to create a simplified standardization for regular and irregular shaped tall buildings that are built in densely areas, as some buildings are shielded and gets little affected by the wind. While others are greatly exposed due to channeling effect (street canyons), caused by other buildings. Furthermore, most international building codes only account for the along-wind loading. And fail to address across-wind, which some cases can become more significant than the along-wind. It also gives less accurate data regarding vortex shedding, torsional loads, wind environment in the streets and lateral acceleration of the building.

However, the revisions of building standards are time consuming, therefore the update process is slow. The European standard (Eurocode) for wind actions on structures (EN 1991-1-4:2005) was released in 2005. In 2010, it underwent some minor changes. No future revisions are planned until 2026 (Appendix A).

CHAPTER 9

CONCLUSIONS

The thesis provided a simplified understanding of the field within wind engineering. Simplified descriptions of wind tunnel testing and CFD simulations regarding tall buildings were given herein. The thesis also present architectural modifications that are used to mitigate wind response on tall buildings.

Due to different configurations (e.g. terrain category, building model characteristics, software packages etc.), comparison of the results would <u>not</u> be precise. However, it is worth mentioning that all building shapes encountered in this thesis have mostly showed significant results regarding reduction of wind response (i.e. across-wind, along-wind, torsional-wind, vortex shedding, among others). Findings are presented below:

- To provide more sustainable and economical buildings, it is advisable to perform wind tunnel and/or CFD simulations for buildings taller than 120 meters.
- The orientation of buildings with respect to the prevailing wind direction will affect the wind response of buildings.
- Dampers such as AMD, AVSD, VD and TMD help to dissipate the kinetic energy, which reduces the lateral movement. TMD provides better habitability and economic benefits for buildings with height greater than 120 meters.
- Tapering reduces along-wind and across-wind response. It also reduces trapping of vortex shedding.
- Setback seems to gain same benefits as tapering regarding across-wind response but has larger trappings of vortex shedding in regions of setbacks.
- Openings reduce wind area, i.e. overall wind effect on a tall building.
- Twisting of 180^o can reduce design wind load up to 30% when compared to square building of same height.
- Corner modifications can reduce across-wind and along-wind, with 40% and 30% respectively.
- Sculptures, fences, podiums, canopies etc. may reduce downdraught- and street canyon effect.
- Most building codes fail to address across-wind.
- Hexagonal model with recessed modifications had tremendous reduction related to pressure coefficient for all faces. Yielding an average reduction of nearly 35% compared to the model without modification.
- Octagonal building showed max. positive C_p at face A (0.835), and max. negative C_p at face D (-0.705).
- E-shaped building showed max. positive C_p at face E (0.8), and max. negative C_p at face A (-0.68).
- L-shaped building showed max. positive C_p at induced wind angel of 45^o (≈ 1.0), and max. negative C_p at induced wind angel of 180^o (- 0.65).
- U-shaped building showed max. positive C_p at induced wind angel of 0^o (≈ 0.9), and max. negative C_p at induced wind angel of 180^o (- 0.80).

CHAPTER 10

FURTHER WORK

Further work should be focused towards updating existing building codes and standards on global and regional levels. Emphases should also be on collecting wind tunnel and CFD results for irregular shaped buildings into a database. This will help engineers build safer and more sustainable buildings in the future.

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Our e-mail to Standard Norge:

Hei!

Vi er 2 studenter ved Universitetet I Stavanger som skrive bacheloroppgaven som omhandler vindbelastninger på bygningstyper som strekker seg utenfor forskriftene i NS1991-1-4:2005+NA:2009 (høyde over 200 meter). Men vi har noen spørsmål knyttet til og rundt NS'en.

Følgende spørsmål lurer vi på:

1. Er det planlagt å implementere bygninger som er over 200 meter i fremtiden?
2. Er det planlagt revisjon/oppdateringer i den gjelden NS'en i nærmeste fremtid?
3. Det stemmer at den ikke er blitt oppdater siden 2004?
4. Er dere i samarbeid med FN ifb med "Sendai Framework for Disaster Risk Reduction" som ble startet i 2015?

Mvh Tor A. Stangeland & Anders R. Meltveit

Answer from Standard Norge:

Hei,

Jeg viser til deres epost under, og jeg har følgende svar på deres spørsmål:

1. I utkast til ny standard som er under utarbeidelse i den europeiske standardiseringsorganisasjonen CEN, er det foreslått å øke grensen til 300 meter.
2. Som nevnt over, revideres nå hoveddelen av standarden. Siden alle standardene i Eurokode-serien er under revisjon, vil mest sannsynlig ikke de nye utgavene bli publisert før alle delene er ferdige. Dette skjer tidligst i 2026. Det norske nasjonale tillegget er også under revisjon, men det planlegges ingen andre endringer enn å implementere ny kommuneinndeling.
3. Hoveddelen av standarden ble publisert i 2005, men det ble utgitt et endringsblad og et rettelsesblad til standarden i 2010. Det nasjonale tillegget ble utgitt i 2009.
4. Jeg kjenner ikke til dette prosjektet. Som sagt utarbeides hoveddelen til standarden på europeisk nivå, og det kan være at noen av de som bidrar på europeisk nivå kjenner til dette.

Hilsen Vivian Meløysund