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A Review on Computational Evaluation of Wind Pressure on Tall Buildings using CFD and Sd

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Abstract: **- Super-tall buildings located in high velocity wind regions are highly vulnerable to large lateral loads. Designing for these structures must be done with great engineering judgment by structural professionals. With the rise of high performance computing nodes, an emerging method based on the numerical approach of Computational Fluid Dynamics has created an additional layer of analysis and loading prediction alternative to conventional methods. The present document study the past research which uses turbulence modeling and numerical algorithms by means of Reynolds-averaged Navier-Stokes and Large Eddy Simulation equations applied to a square prismatic prototype structure in which its dynamic properties have also been investigated. With proper modeling of the atmospheric boundary layer flow, these numerical techniques reveal important aerodynamic properties and enhance flow visualization to structural engineers in a virtual environment. This paper presents the results of an overview of different research works to be done regarding the study of wind pressure evaluation on tall building using Computational Fluid Dynamics.**

***Key Words: Wind Pressure, Tall Building, CFD, Lateral Loads*.**

1. INTRODUCTION:

The development of new construction techniques in the 20th century has created structures that are flexible, low in damping, and relatively light in weight which therefore exposes the structure to the effect of wind acting upon it. Wind engineering has been the field with the aim of primarily developing tools to better understand the action of the fluid on the structure with origins that could be traced back to the 1960s.

The development of knowledge found in the present literature regarding this subject has lead structural engineers to design and ensure the performance of the structure subjected to the action of wind to be within adequate limits during the lifetime of the structure in structural safety and serviceability criteria (Simiu and Scanlan 1978).

2. REVIEW OF LITERATURE:

2.1. Overview

Wind is composed of a multitude of eddies of varying sizes and rotational characteristics carried along in a general stream of air moving relative to the earth's surface. These eddies give wind its gusty or turbulent character. Wind interaction with surface features gives rise to the gustiness of strong winds in the lower levels of the atmosphere. The average wind speed over a time period of the order of ten minutes or more tends to increase with height, while the gustiness tends to decrease with height. There are several different phenomena giving rise to dynamic response of structures in wind. These include buffeting, vortex shedding, galloping and flutter. Slender structures can be sensitive to dynamic response in line with the wind direction as a consequence of turbulence buffeting. Transverse or cross-wind response is more likely to arise from vortex shedding or galloping but may also result from excitation by turbulence buffeting. Flutter is a coupled motion, often being a combination of bending and torsion, and can result in instability. For building structures flutter and galloping are generally not an issue. An important problem associated with wind induced motion of buildings is concerned with human response to vibration and perception of motion. Humans are very sensitive to vibration to the extent that motions may feel uncomfortable even if they correspond to relatively low levels of stress and strain. Therefore, for most tall buildings serviceability considerations govern the design and not strength issues (Mendis et al. 2007).

2.2. Wind Effect on Structure

The greatest probability of damage to structures has been presented by Davenport (1963) to be the case of strong winds with neutral atmospheric conditions. Davenport suggests that structural response to repeated loads of successive gusts is an important factor in the design of tall buildings. Repeated loading may lead to fatigue, failure, foundation settling, excessive deflections causing cracking to building elements, or induced motion that may affect the comfort of the occupants of the structure. A building can be considered to have failed if it becomes unserviceable due to the action of repeated loads or the action of a single large load of great magnitude. It is very important that the fluctuating loads caused by wind on a structure play an important role in the design and analysis of tall buildings, especially structures with large aspect ratios (Reinhold 1977). The primary concern for a structural engineer when studying wind phenomena, around a building, is the mean velocity profile of the wind. Moreover, two aspects of turbulent flows are of interest to the engineer: (a) the state of turbulence of the natural wind approaching a structure, and (b) the local turbulence provoked in the wind by the structure itself. Most structures in civil engineering present bluff forms, in wind engineering studies we focus on the bluff-body aerodynamics aspects of the wind and structure interaction. This has led the industry to further research on the details of flow effects around bluff bodies such as tall buildings. This finally leads to the interest of the engineer in the study of the development of body pressures by the flow acting around a structure (Simiu and Scanlan 1978).

2.3. Wind Damaged Structures

Damage to buildings and other structures by windstorms has been a fact of life for human beings from the time they moved out of cave dwellings to the present day. Trial and error has played an important part in the development of construction techniques and roof shapes for small residential buildings, which have usually suffered the most damage during severe winds. In past centuries, heavy masonry construction, as used for important community buildings such as churches and temples, was seen, by intuition, as the solution to resist wind forces. For other types of construction, windstorm damage was generally seen as an 'act of god', as it is still viewed today by many insurance companies.

The nineteenth century was important as it saw the introduction of steel and reinforced concrete as construction materials, and the beginnings of stress analysis methods for the design of structures. The latter was developed further in the twentieth century, especially in the second half, with the development of computer methods. During the last two centuries, major structural failures due to wind action have occurred periodically, and provoked much interest in wind forces by engineers. Long-span bridges often produced the most spectacular of the failures, with the Brighton Chain Pier, England in 1836, the Tay Bridge, Scotland in 1879, and Tacoma Narrows Bridge, Washington State, U.S.A. in 1940 being the most notable, with the dynamic action of wind playing a major role (Holmes 2007). Other large structures have experienced failures as well for example, the collapse of the Ferry bridge cooling towers in the United Kingdom in 1965, and the permanent deformation of the columns of the Great Plains Life Building in Lubbock, Texas during a tornado in 1970. These events were notable, not only as events in themselves, but also for the part they played as a stimulus to the development of research into wind loading in their respective countries.

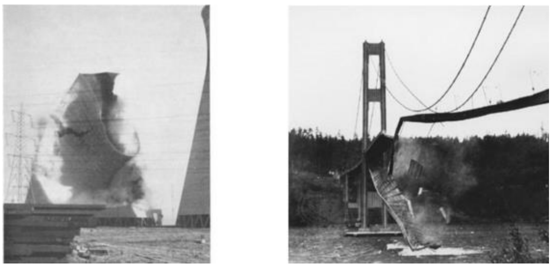

Figure 2: (a) Moment of collapse of Cooling Tower 2A, U.K. (b) Collapse of midsection of Tacoma Narrows Bridge, WA

Some major windstorms, which have caused large scale damage to residential buildings, as well as some engineered structures, are also important for the part they played in promoting research and understanding of wind loads on structures. The effects of Hurricane Andrew in Florida proved to be the costliest natural disaster in the state's history. Andrew made landfall near Homestead, Florida on August 24, 1992 as a Category 5 hurricane. Strong winds from the hurricane affected four southeastern counties of the state in which it damaged or destroyed 730,000 houses and buildings. The hurricane caused about $25 billion in damage and 44 deaths. The first 'tall buildings' to appear in Japan might be the traditional wooden pagodas which are seen in historic Japanese cities such as Nara and Kyoto. Strong typhoons could cause damage to pagodas. The 5-story, 47.8 m (157.8 ft.) high Shiten'noji Pagoda collapsed due to typhoon Muroto on September 21, 1934. The maximum peak gust speed was estimated to be more than 60 m/s (134.2 mph) and was accompanied by a high tidal wave of more than 4 meters (13.1 ft.). Thus, the history of the development of design and construction methods for tall buildings was a record of fights with strong winds. There are many wind related problems in construction of tall buildings, but the main problem for engineers is their capability of resistance to wind forces, because higher altitudes mean higher wind speeds, and consequently higher wind forces (Tamura 2009).

Figure 3: (a) Shiten'noji Pagoda collapse in 1937 and (b) Present day rebuilt structure

As well as damage to buildings produced by direct wind forces –either overloads caused by overstressing under peak loads, or fatigue damage under fluctuating loads of a lower level, a major cause in severe wind storms is flying debris. Penetration of the building envelope by flying 'missiles' has a number of undesirable results: high internal pressures threatening the building structure, wind and rain penetration of the inside of the building, the generation of additional flying debris, and the possibility of flying missiles inside the building endangering the occupants. The area of a building most vulnerable to impact by missiles is the windward wall region, although impacts can also occur on the roof and side walls. As the air approaches the windward wall, its horizontal velocity reduces rapidly. Heavier objects in the flow with higher inertia will probably continue with their velocity little changed until they impact on the wall. Lighter and smaller objects may lose velocity in this region or even be swept around the building with the flow if they are not directed at the stagnation point (Holmes 2007). One Indiana Square is a 36-story (504 ft) tall building located in downtown Indianapolis, Indiana. The building went exterior remodeling after damage by tornado-strength winds reaching speeds exceeding 130 km/h (80.7 mph) that occurred on April 2, 2006. This particular storm brought winds sufficient to cause severe damage to the façade and structural elements of 16 out of 36 stories of the tower causing millions of dollars in monetary loss and the closing of street sand businesses for several days. The nature of the damage prompted debate about whether the damage was caused by tornado, downburst, or extreme straight wind conditions. The recorded wind speed was very close to typical design wind speed for buildings. The recommended speeds are dependent upon geographic locations in which the region of southeast Florida has the highest wind speed values. After the 2006 damage, design of a new façade with curtain wall to be installed over the existing façade was released in 2007 by the integrated design firm Gensler. The new façade after the re-cladding process essentially put another layer of skin around the building's exterior face by expanding it by 18 in. around its perimeter (Yilmaz and Duffin 2014).

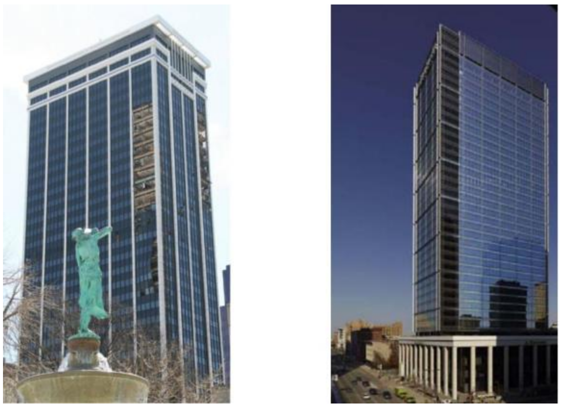

Figure 4: (a) One Indiana Square tornado induced damage (b) Remodeled façade of building

2.4. Computational Wind Engineering

The historical starting point of CWE could be situated around 1963 when Smagorinsky developed one of the first successful approaches to Large Eddy Simulation (LES), the Smagorinsky-Lilly model, which is still intensively used in many areas of fluid mechanics today. The main research area of Smagorinsky was Numerical Weather Prediction applied at the meteorological macro scale of particular importance for CWE were the pioneering studies by Meroney and his co-workers in which a hybrid approach was pursued for the systematic comparison of numerical simulations with dedicated wind tunnel measurements in atmospheric boundary layer wind tunnel (Meroney and Yamada 1971, Yamada and Meroney 1972, Derickson and Meroney 1977). In Aerospace Engineering, the T3 group at the Los Alamos National Laboratories in 1963 first used computers to model the 2D swirling flow around an object using the vortices stream function method, followed by the first 3D application by Hess and Smith (1967) using the so called panel method. Driven by these early achievements, early efforts in CWE focused on the determination and analysis of wind velocity and pressure field around buildings (Blocken 2014). The difference in time between the earliest CFD developments in the 1950s and the later application of CFD in CWE for wind velocity and pressure fields around buildings is attributed to the specific difficulties associated with the flow around bluff bodies with sharp edges. Murakami (1998) diligently outlined some of the difficulties encountered in CWE: (1) high Reynolds numbers in wind engineering applications, necessitating high grid resolutions, especially near wall regions as well as accurate wall functions, (2) the complex nature of the 3D flow field with impingement, separation and vortex shedding, (3) the numerical difficulties associated with flow at sharp corners and consequences of discretization schemes, and (4) the inflow and outflow boundary conditions which are particularly challenging for LES. These difficulties were directly linked to limitations in physical modeling and in computational requirements at those times, but many of those limitations are still to some extent present today. CWE is complementary to other, more traditional areas of wind engineering, such as full scale onsite experimentation and reduced scale wind tunnel testing. Each approach has its specific advantages and disadvantages. The main advantage of on-site measurements is that they are able to capture the real complexity of the problem under study. To name a few, important disadvantage are that they are not fully controllable due to the inherently variable meteorological conditions, that they are not possible state in the design stages of the building, and that usually only point measurements are performed. The latter disadvantage also hold true for wind tunnel measurements. Techniques such as Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF) in principle allow planar or even full 3D data to be obtained in wind tunnel tests, but the cost is considerably higher and application for complicated geometries can be hampered by laser-light shielding by the obstructions constituting the model. Another disadvantage is the required adherence to similarity criteria in reduced scale testing, which can limit the extent and the range of problems that can be studied in wind tunnels. In addition, it is widely recognized that the results of CFD simulations can be very sensitive to the wide range of computational parameters that have to be set by the modeler. For typical simulations, the user has to select target variables, the approximate form of the governing equations, the turbulence model, the computational domain, the computational grid, the boundary conditions, the discretization schemes, the convergence criteria, etc. Therefore this expresses the need for best practice guidelines for CWE. CWE has grown to a strongly established field in wind engineering research, practice and education. It is employed daily by probably thousands of researchers, practitioners and teachers all over the world.

2.4.1. Micro scale and CFD

At the micro scale, the flow around surface mounted obstacles such as buildings is explicitly resolved, i.e. these obstacles are represented with their actual shape. Yamada and Meroney (1972) studied 2D airflow over a square surface mounted obstacle in a stratified atmosphere, both in the wind tunnel and with CFD. Hirt and Cook (1972) calculated 3D flow around structures and over rough terrain. CFD simulations around 3D buildings started with fundamental studies of isolated buildings, often with a cubical shape, to analyze the velocity pressure fields (Murakami and Mochida 1988, 1989; Baskaran and Stathopoulos 1989, 1992). Together with later studies they laid the foundations for the current best practice guidelines by focusing on the importance of grid resolution, the influence of boundary conditions on the numerical results, and by comparing the performance of various types of turbulence models in steady RANS simulations. Also steady RANS versus LES studies were performed (Blocken 2014). In the past, especially the deficiencies of the steady RANS approach with the standard κ-ε model (Jones and Launder 1972) for wind flow around buildings were addressed. These include the stagnation point anomaly overestimation of turbulent kinetic energy near the frontal corner and the resulting underestimation of the size and separation and recirculation regions on the roof and the side faces, and the underestimation of turbulent kinetic energy in the wake resulting in an overestimation of the size of the cavity zone and wake. Various revised linear and non-linear κ-ε models and also second-moment closure models were developed and tested and showed improved performance for several parts of the flow flied. However the main limitation of steady RANS modeling remained: its incapability to model the inherently transient features of the flow field such as the separation and recirculation downstream of windward edges and vortex shedding in the wake. These large-scale features can be explicitly resolved by LES. The studies by Murakami et al. (1987), later by Murakami et al. (1990, 1992) illustrated the intrinsically superior performance of LES compared to RANS. Nevertheless, LES entails specific disadvantages that are not easy to overcome, including the strongly increased computational requirements and the difficulty in specifying appropriate time-dependent inlet and wall boundary conditions (Blocken 2014).

2.4.2. Reduced-scale Wind Tunnel Testing and CWE

In the past decades, often statements have been made that CFD would replace reduced scale wind tunnel testing and that it would be the numerical wind tunnel. Many scholars such as Castro and Graham (1999) and Stathopoulos (2002) convincingly denounced the label without recognizing the important complementary value and potential of CWE. The complementary aspects of wind tunnel testing and CWE are multifold. Wind tunnel testing can provide the indispensable high-quality validation data needed for CWE, and CWE can supplement wind tunnel testing by providing whole flow field data on all relevant parameters. Leitl and Meroney (1997) indicated the value of CFD to design wind tunnel experiments by using numerical codes that can help design and setup wind tunnel experiments which can reduce the time required to optimize a physical model and expensive pre-runs in a wind tunnel. Moonen et al. (2007) developed a series of new indicators for wind tunnel test section flow quality and applied CFD to illustrate the effectiveness of these indicators. This approach was adopted by Calautit et al. (2014) for further development of design methodologies of closed-loop subsonic wind tunnels (Blocken 2014).

2.5. Wind Tunnel Measurements

Wind tunnel tests are powerful tools that give engineers the ability to estimate the nature and intensity of wind forces acting on complex structures such as tall buildings. Wind tunnel testing is especially useful when the surrounding terrain and the shape of the structure causes complex wind flows that are not fully addressed by simplified codes (Samali et. al.2004). Many studies have been performed in the measurements of wind loads on structures by either using full-scale measurements or by wind tunnel model studies. As technology has advanced, the estimation of these forces has increased in reliability. Wind loads are particularly important for flexible structures such as tall-buildings with low damping. Typically, wind tunnel measurements are performed in boundary-layer wind tunnels that are capable of developing flow conditions that meet these conditions (Taranath 2005):

1. The natural atmospheric boundary layer is modeled as such to account for the variation of wind speed with height
2. The length scale of atmospheric turbulence is approximately the same scale as of that of the building.
3. The model building and surrounding topography are geometrically similar to the full-scale.
4. The pressure gradient in the longitudinal direction is accounted for Reynolds number effects on pressures and forces are kept to a minimum.
5. Response characteristics of the instrumentation are consistent with the measurements to be taken.

The wind tunnels have generally these test-section dimensions: width of 9 to 12 feet, height of 8 to 10 feet, and length of 75 to 100 feet. Wind speeds that can be generated in these tunnels can range from 25 to 100 miles per hour (Taranath 2005). Typically there are two types of test models being used to conduct studies: the first one is the rigid High Frequency Base Balance Model (HFBBM), and the second being the aero-elastic Model (AM). The models can be used independently or combined to obtain design loads for a structure. The HFBBM measures overall fluctuating loads for the determination of dynamic responses. The aero elastic model is employed for direct measurements of loads, deflections and accelerations when the lateral motions of a building are considered to have a large influence on the loading produced by the wind. Numerous techniques are used in these wind tunnels to generate the turbulence and atmospheric boundary layer by using tools such as spires and grids. In long wind tunnel sections, turbulent boundary layer is generated by providing roughness elements in the approaching flow. Although these techniques are considered to be appropriate, there are concerns in whether the wind turbulence is appropriately modeled. Typically the scaling used to account for all these variables varies in the order of 1:400 to 1:600 for urban environments (Taranath 2005). Reinhold (1977) investigated several problems associated with the measurements of fluctuating wind loads on tall structures using a number of building orientation and configurations. The author generated atmospheric winds over urban areas in a short-test section tunnel and presented the results in the document. In the study, a simple square prism was used because of its simplicity. Reinhold's study extended measurements of these random loads at multiple levels that improved with the respect of the placement of pressure transducers along the model structure. It must be noted that most complete wind tunnel tests and reports which have been conducted in the past that are of aid to design engineers are often considered proprietary and are almost never published (Reinhold1977).

2.6. Overview of Tall Buildings

Tall towers and building have fascinated mankind from the beginning of civilization, their construction being initially for defense and subsequently for ecclesiastical purposes. The growth in modern tall building construction which began in the late part of the 19th century has been largely for commercial and residential purposes. Tall

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commercial buildings are primarily a response to the demand by business activities to be as close to each other, and to the city center, as possible, thereby putting intense pressure on the available land space. Tall commercial buildings are frequently developed in city centers as prestige symbols for corporate organizations. Furthermore, the business and tourist community has fuelled a need for more frequently city center hotel accommodations such as high rises. The rapid growth of the urban population and the consequent pressure of limited space have influenced city residential developments. The high cost of land, the desire to avoid continuous urban sprawl, and the need to preserve important agricultural production have all contributed to drive residential buildings vertically. Also, some topographical conditions make tall buildings the only feasible solution for housing needs such as the ones encountered in Hong Kong and Riode Janeiro.

2.6.1. Factors Affecting Growth, Height, and Structural Form

The feasibility and desirability of high-rise structures have always depended on the available materials, the level of construction technology, and the state of development of the services necessary for the use of buildings. Significant advances have occurred with the advent of a new material, construction facility, or form of service. The socioeconomic problems that followed industrialization in the nineteenth century coupled with an increasing demand for space in U.S. cities created a strong stimulus to tall building construction. The growth could not have been sustained without two major technical innovations that occurred in that century:

1. The development of higher strength and structurally more efficient materials, wrought iron and thereafter steel.
2. The introduction of the elevator.

For the first time, this made upper stories as attractive to rent as the lower ones and made the taller buildings financially viable. The new materials allowed the development of lightweight skeletal structures permitting buildings of greater height and with larger interior open spaces and windows. Improved design methods and construction techniques allowed the maximum height of steel frame structures to reach a height of 60 stories with the construction of the Woolworth Building in 1913. This golden age of skyscraper construction culminated in 1931 with its crowning glory, the Empire State Building, whose 102-story brace steel frame reached a height of 1250ft. (381 m).

Figure 5: (a) Woolworth Building, NY (b) Empire State Building, NY

Reinforced concrete construction began around the turn of the 20th Century but it has only been used for the construction of multistory buildings approximately after the end of World War I. The inherent advantages of the composite material which could be readily formed to simultaneously satisfy both aesthetic and load-carrying requirements were not fully appreciated by then due to limited design knowledge of the material. The economic depression of the 1930s put a hold to the great skyscraper era and it was only after some years passed after World War II that the construction of high-rise buildings recommended with new structural and architectural solutions. Different structural systems have gradually evolved for residential and office buildings, reflecting their differing functional requirements. In modern office buildings, the need to satisfy the differing requirements of individual clients for floor space arrangements led to the provision of large column-free open areas to accommodate flexibility in planning. Other architectural features of commercial buildings that have influenced structural form are the large entrances and open lobby areas at ground level, the multistory atriums, and the high-level restaurants and viewing galleries that may require more extensive elevator systems and associated sky lobbies. A residential building's basic functional requirement is the provision of self-contained individual dwelling units, separated by substantial partitions that provide adequate acoustic and fire insulation. Because partitions are repeated from floor to floor, modern designs have utilized them in a structural capacity leading to the shear wall, cross wall, or in filled-frame forms of construction. The trends to exposed structure and architectural cutouts, and the provision of setbacks at upper levels to meet daylight requirements have also been features of modern architecture. The requirement to provide adequately stiff and strong structures led to the development of a new generation of structural framing such as braced frames, framed-tube and hull-core structures, wall-frame systems, and outrigger-braced structures (Stafford Smith and Coull 1991). The latest generation of buildings with their more varied and irregular external architectural treatment has led to a hybrid double and sometimes triple combinations of the structural forms for modern buildings.

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2.6.2. Criteria for the Definition of Tall Buildings

The Council on Tall Buildings and Urban Habitat (CTBUH) has developed a guideline to define what constitutes a "tall building" that exhibits some element of height in one of these three categories:

1) Height relative to context: it is not just about height but about the context in which it exists. A 20-story building may not be considered a tall building in a high-rise city such as New York or Hong Kong, but in a provincial city or suburb this may be distinctly taller than the urban norm.
2) Proportion: a tall building is not just about height but also proportion. There are a number of buildings which are slender enough to give appearance of a tall building against the background of a low urban environment. On the other hand, there are numerous large foot prints which are quite tall but their floor area rules them out as being classified as a tall building.
3) Tall building technologies: If a building contains technologies which may be attributed as being a product of tallness such as high speed elevators and wind bracing, then this building can be classified as a tall building.

The number of floors if a poor indicator of defining a tall building due to the changing nature of floor to floor height between different buildings uses. A building of perhaps 15 or more stories, or over 50 m (165 ft.) in height could be used as a threshold for considering it a "tall building." However, the CTBUH defines a "super tall" building over 300 meters (984 ft.) in height, and a "mega tall" as a building over 600 meters (1,968 ft.) in which it recognizes building height in three categories. As of August 2014 there exists 82 super tall and 2 mega tall buildings that have been completed and are presently occupied (CTBUH 2014).

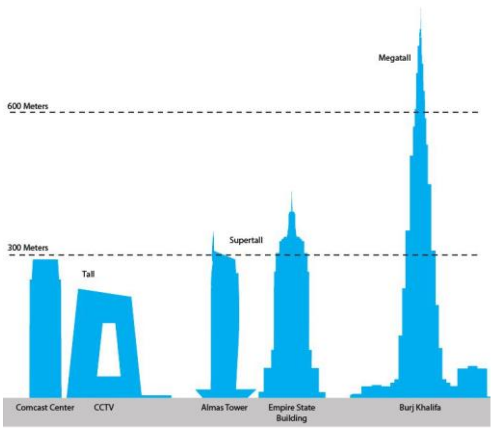

Figure 6: Comparison of tall, super tall and mega tall building height criteria

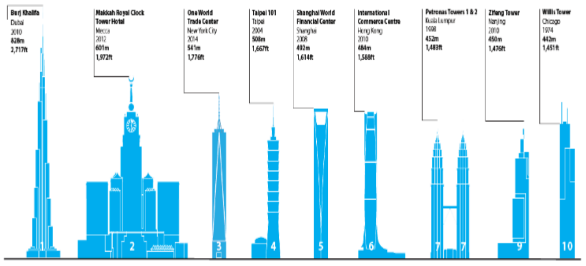

Figure 7: World's ten tallest buildings according to 'height to architectural top' as of November 2014

3. CONCLUSION:

Wind is a phenomenon of great complexity arising from the interaction of wind with structures. Simple quasi-static treatment of wind loading, which is universally applied to design of typical low to medium-rise structures, can be very conservative for design of very tall buildings. Important factors in wind design of tall buildings are dynamic response (effects of resonance, acceleration, damping, structural stiffness), interference from other structures, wind directionality, and cross wind response. Mendis et al. (2007) considered a number of key factors associated with the design of tall buildings to the effects of wind loading. The general design requirements for structural strength and serviceability assume particular importance in the case of tall building design. Significant dynamic response can result from both buffeting and cross-wind loading excitation mechanisms. Serviceability with respect to occupier perception of lateral vibration response can govern the design. The authors have suggested a specific purpose designed damping system in order to reduce these vibrations to acceptable levels. Dynamic response levels also play an important role in the detailed design of façade systems. State of the art boundary layer wind tunnel testing, for determining global and local force coefficients and the effects of wind directionality, topographical features and nearby structures on structural response are identified to be quite useful to tall building design. The emerging use of CFD codes, particularly at the concept design stage, is also noted as assuming increasing importance in the design of tall buildings. The authors have suggested that the design criteria for lateral wind loads shall consider stability against overturning, uplift and or sliding of the structure as a whole, strength of the structural components of the building, and serviceability so as to restrict the inter storey and overall deflections within acceptable limits.

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