COMPARISON OF WIND LOAD ANALYSIS ON LOW RISE BUILDINGS BY USING DIFFERENT DESIGN CODES.

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Abstract

Internal and external pressures that develop as wind interacts with buildings have been incorporated into standards to guide designers to compute proper reinforcement to resist induced loads by the wind during the buildings design life. Kenya is yet to develop its wind loading standard and most buildings are designed according to various international wind loading standards such as ***CP3*** and ***BS6399***. However, these wind code have not been updated in some aspect in the last few years and are being superseded. To this aim, a comprehensive comparison of similarities and differences in the performance of provision for wind load analysis on a low-rise building of three updated standards ***(ENV1991-2-4_2005)***, ***(AS1170.2-2011)*** and ***(ASCE 7-2005)*** versus the currently in use standards in Kenya was conducted and presented in this paper. Collating was broken down into comparison of basic parameters, equations, coefficient factors and along-wind, across-wind response of two case study building. It was observed that variations in definition of wind field characteristics were the primary contributors to varying wind responses and parameters associated with wind velocity contributed mostly towards differences in the wind responses. It was therefore recommended that wind field definitions and characteristics need to be harmonized.

Keywords: Wind loads, design standards

1. Introduction

Wind study is important to understand the possible damage, inconvenience or benefits which may result from wind interaction to the built environment (Cermak, 1975, p. 9). The resulting force that acts on buildings elevations as wind blows against the surfaces of the building, is called “wind load” (Cermak, 1975, p. 9). This load must be absorbed safely by the building’s structure and transferred efficiently to the foundation of the building to avoid structural collapse. Investigation on numerous cases of building damages and even collapse show that, while many failures are undoubtably due to defects of workmanship, some cases of damage results from under-estimation of wind forces and that is frequently due to the lack of appreciation by designers on the significance of gust action and ultimately wind loading on buildings and more so on low rise buildings.

In structural design, buildings are under many kinds of loadings; ranging from dead load to live load. Besides these loads, wind load is also a critical loading that needs to be considered especially so for a low-rise building since most low-rise buildings are immersed within the aerodynamic roughness on the earth’s surface where turbulent intensities are rather high (Smith et al., 2016). Low-rise buildings are less sensitive to wind loads compared to high-rise buildings that are subjected to wind loads of the same magnitude. Thus, designers are conservatively more concerned about vertical loads than the lateral loads when dealing with low and medium-rise buildings(Holmes et al., 2009). In doing so, these buildings are subjected to risk when extreme wind conditions impose large wind loads on the building.

The collating of five internationally recognized and used standards is important to understand the measure of sophistication achieved in addressing wind load by each standard and the underlying similarities in the parameters, equations and procedures described in each standard. Additionally, designers, researchers and engineering students will be able to know which country-specific factors and parameters originally designed for the native country of the standard can or cannot be directly adopted for use in Kenya for design purposes while using these standards. Furthermore, this research will highlight the performance of the provisions in the five standards on a low-rise building which will in turn help in the development of an international wind loading standard.

The Kenyan wind speed map that shows the basic wind speeds was developed in the 1970s and has never been updated since then (E. O Ong’ayo, S.K Mwea, 2014). Additionally, the wind speed map was based on thirty years of windspeed data collection resulting in the underestimation of wind speeds which in turn affects the wind loads subjected to buildings over their design life.

2. Methodology

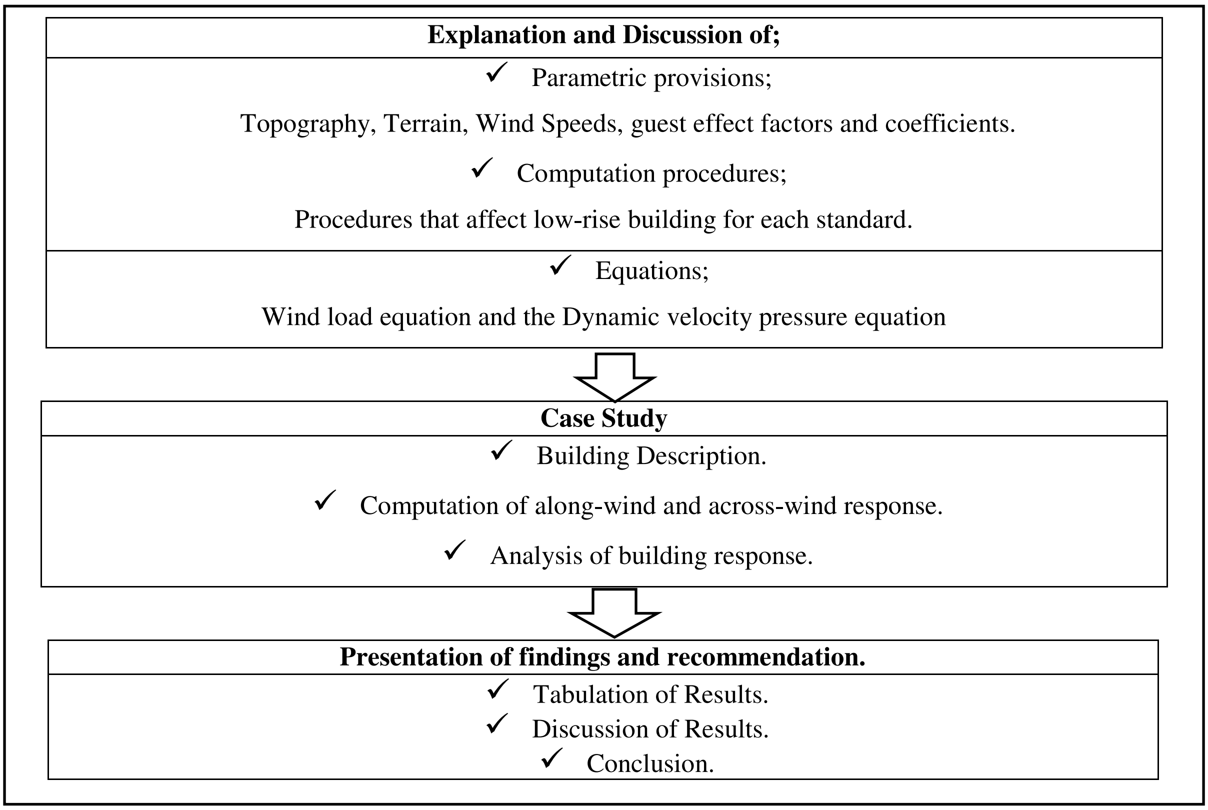

Fig. 1. Summary of methodology

a. Comparison of parameters

The provisions in the five standards uses different terminologies to describe similar parameters

Table 1. Parameter definition

Variable	Definition
P	Wind Pressure/ Load.
q, $q_{ref,}$ qh	Dynamic Velocity Pressure.
Cp, Cpe, Cpi, Cpf	Internal and External Pressure Coefficients.
Ce (Ze)	Exposure Coefficient
Ca	Shape factor
Cd, Cdyn	Dynamic Effect factor.
Cf	Force coefficient
Cfig	Aerodynamic Shape factor
Aref	The reference Area.

In wind load computation, the reference wind speed is the most important parameters. Across the five standards their provision is defined differently. For instance, BS 6399 uses mean hourly wind speed while ENV 1991-2-4 adopts a 10-minute mean speed-gusts as its reference wind velocity while CP3–4–2: *1972,* ASCE 7-*2005* and AS/NZS1170.2-*2011* as summarized in table 2.

Table 2. Reference wind speed for the five standards.

Standard	Wind speed Definition	Reference Height	Recurrence Interval
CP3–4–2: *1972*	3-second gust speed	10m above ground in an open ground.	Return period of 50 years.
BS6399–2:*1997*	Hourly mean wind speed	10 m over completely flat terrain.	Return period of 50 years.
ENV 1991-2-4*:2005*	10 minutes mean wind velocity	10 m above ground level in open country terrain.	Return period of 50 years.
ASCE 7-*2005*	3-second gust speed	10m above the ground in an open terrain	Return period of 50 years.
AS/NZS1170.2-*2011*	3-second gust wind	10m above ground level.	Return period of 50 years.

The topography factor accounts for wind speed-up over hills, ridges and escarpments and it is related to the reference wind speed at the base of these features. This factor has been provided only by the ENV 1991-2-4:2005, ASCE 7-2005, AS/NZS1170.2-2011 as showed in table 3.

Table 3. Topography factor

Standard	Roughness Category
CP3–4–2: *1972*	None
BS6399–2:*1997*	None
ENV 1991-2-4*:2005*	$Ct = 1$ for $\Phi<0.05$ $Ct = 1+2$ for $\Phi<0.3$ Where Φ is the upwind slope. $Ct = 1+0.6$ for $\Phi>0.3$
ASCE 7-*2005*	$Kzt = (1+K_1K_2K_3)^2$ Where $K_1K_2K_3$ are given.
AS/NZS1170.2-*2011*	$Mt = M_hM_{lee}(1+0.00015E)$ Where; M_h is the hill multiplier M_{lee} is the lee effect multiplier E is the site elevation above mean sea level

i. Internal and External Pressure Coefficients.

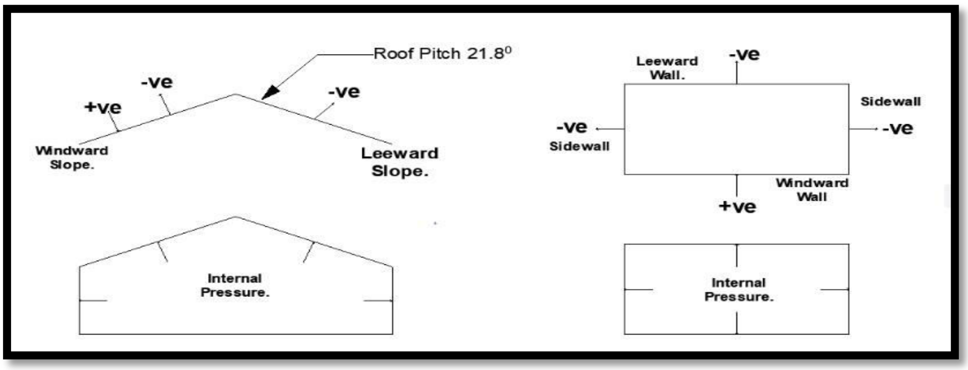

Fig. 2. Pressure coefficients for basic building shapes

The five standards give pressure coefficients for basic building shapes in the form of tables and graphs. They have adopted the same sign convention where; + (plus sign) means positive pressure acting towards the surface while – (minus sign) means negative pressure acting away from the surface as illustrated in the fig. 2.

ii. Terrain factor

The terrain factor modifies the basic wind speed to account for the variation of terrain and height. It also accounts for the variations of mean wind velocity due to its height above the ground level whereas the topography factor modifies the basic wind speed for sudden changes occurring in the topography such as increase of mean wind speed over isolated hills and escarpments.

Table 4. Terrain and roughness factor for the five standards.

Standard	Roughness Category
CP3–4–2: *1972*	Ground roughness 1 = *(open country no obstructions)* Ground roughness 2 = *(open country scattered windbreakers)* Ground roughness 3 = *(country with many windbreaks)* Ground roughness 4 = *(surface with large and frequent obstructions)*
BS6399–2:*1997*	Provides a table*(table4)* for sites in country and town terrain. Generally, the equation for computing the Sb is given as; Sb=Sc{1+(gt*St) +Sb} for country terrain. And Sb=ScTc{1+(gt*St*Tt) +Sb} for town terrain.
ENV 1991-2-4*:2005*	Terrain Category1 = *(open sea, lakes and smooth flat country without obstacles.)* Terrain Category 2 = *(farmland without boundary hedge, occasional small farm structures, houses or trees)* Terrain Category 3 = *(suburban or industrial area permanent forests)* Terrain Category 4 = *(urban areas in which at least 15% of the surface is covered with buildings. and their average heights exceed 15m)*
ASCE 7-*2005*	Roughness Category A – *large city centers.* Roughness Category B – *urban, suburban, wooded area or any terrain with numerous closely spaced obstructions)* Roughness Category C – *open terrain with scattered obstructions having height generally less than 9.1m* Roughness Category D – *flat, unobserved areas and water faces outside hurricane-prone regions*
AS/NZS1170.2-*2011*	Category 1 – *exposed open terrain with few or no obstructions and water surfaces at serviceability wind speed.* Category 2 – *water surfaces, open terrain, grassland with few, well-scattered obstructions having heights generally 1.5m to 10m.* Category 3 – *terrain with numerous closely spaced obstructions 3m to 5m high, suburban areas.* Category 4 – t*errain with numerous large high 10m to 30m and closely spaced obstructions, such as large city centers and well-developed industrial complexes.*

iii. Wind Load Computation Comparison

The five standards use different levels of approach to calculate wind load: simple procedure, standard method, detailed procedure, and wind tunnel tests. The scope of this research limited the study to the detailed, standards and simple procedure. Procedures that provide provisions to design for low-rise building were only considered and are presented in table 5 for each of the five standards.

Table 5. Wind load computation procedures for the five standards

STANDARD	PROCEDURE/ METHOD	EQUATION
CP3–4–2: *1972*	Simple	P = q × Cp
BS6399–2:*1997*	Standard Method	P = q× Cp × Ca
	Directional method	P = q × Cp
ENV 1991-2-4*:2005*	Simple Procedure.	P = q_{ref} × Ce (Ze) × Cp
	Detailed Procedure.	P = q_{ref} × Cd × Cf × A_{ref}
ASCE 7-*2005*	Special Low-Rise Method	P = qh [GCpf - GCpi]
	All Heights Method	P = qGCpe – qhGCpi
AS/NZS1170.2-*2011*	Standard Method	P = q × Cfig × Cdyn

iv. Dynamic Velocity

The dynamic velocity pressure for the five standards are described by the equations in table 6;

Table 6. Dynamic velocity pressure equation

Standard	Dynamic Velocity Equation.
CP3–4–2–3: *1972*	$q= 0.613\times(S_1S_2S_3\times Vref)^2$ Where, $\mathbf{S_1}$ is the topography factor $\mathbf{S_3}$ is the probability factor. $\mathbf{S_2}$ is the ground roughness, building size and height factor. $\mathbf{V_{ref}}$ is the refence wind speed.
BS6399–2:*1997*	$q= 0.613\times S_b\times(S_a\times S_d\times Ss\times S_p\times Vref)^2$ Where, $\mathbf{S_b}$ is the terrain factor. $\mathbf{S_a}$ is the altitude factor. $\mathbf{S_d}$ is the directional factor. $\mathbf{S_s}$ is the seasonal factor. $\mathbf{S_p}$ is the seasonal factor. $\mathbf{V_{ref}}$ is the basic reference wind speed.
ENV 1991-2-4*:2005*	$q_{ref} = 0.625\times(C_r\times Ct\times C_{DIR}\times C_{TEM}\times C_{ALT}\times V_{ref})^2$ Where, $\mathbf{C_r}$ is the roughness coefficient. $\mathbf{C_t}$ is the topography coefficient. $\mathbf{C_{DIR}}$ is the directional factor. $\mathbf{C_{TEM}}$ is the seasonal temporary factor. $\mathbf{C_{ALT}}$ is the altitude factor. $\mathbf{V_{ref}}$ is the reference wind speed
ASCE 7-*2005*	$q_z= 0.613\times K_z\times Kzt\times K_d\times V^2$ Where, $\mathbf{K_z}$ is the velocity pressure exposure coefficient. $\mathbf{K_{zt}}$ is the topographic factor. $\mathbf{K_d}$ is the wind directional factor. **V** is the reference wind speed.
AS/NZS1170.2-*2011*	$q= 0.5\times1.2\times(M_d\times M_z\times M_s\times M_t\times V_R)^2$ Where, $\mathbf{M_d}$ is the directional multiplier. $\mathbf{M_z}$ is the terrain and height multiplier. $\mathbf{M_s}$ is the shielding multiplier. $\mathbf{M_t}$ is the topographic multiplier. $\mathbf{V_R}$ is the reference wind speed.

3. Results

This study was therefore aimed to compare the wind load analysis adopted by five standards in computing wind load. A quantitative comparison was also conducted by subjecting two building structures to a 45m/s three second wind guest with an annual probability of 0.02 and comparing the along-wind and across-wind responses.

Given that other standards use the mean hourly and 10-minute mean speed gusts for their reference wind velocities the 45m/s, 3-second gust wind speed had to be adjusted for gust duration to the appropriate reference velocities.

For BS6399 the 3-second gust wind speed was converted in to mean hourly wind speed using the method proposed by (Nicholas J. Cook, 1999). According to Cook's method, the mean hourly wind speed (Vmean)can be calculated from gust wind speed (VG) as shown in the equation below.

$$Vmean = VG/Sb \qquad \textbf{Equation 1}$$

Where, Sb – is the terrain and building factor at 10 m height in open terrain as given in Table 4 of BS6399-2:1997. A value of 1.62 was used for the portal frame warehouse and 1.85 for the 10-storey building.

For ENV 1991-2-4 the mean hourly wind speed was then converted into 10 minutes average wind speed by using factor 1.06 as proposed by the Institute of Civil Engineers in United Kingdom (ICEUK). For the remaining three standards the 45 m/s gust wind speed was directly adopted.

Table 7. Wind speeds for the different averaging times

Wind Speeds(m/s).	Portal frame warehouse	Ten story building
CP3–4–2–3: *1972*	45	45
BS6399–2:*1997*	28	24
ENV 1991-2-4*:2005*	29	25
ASCE 7-*2005*	45	45
AS/NZS1170.2-*2011*	45	45

Wind load calculation for both buildings is given in the appendices. In this section values of importance have been selected for discussion purposes illustrating wind load in the along-wind and across-wind directions.

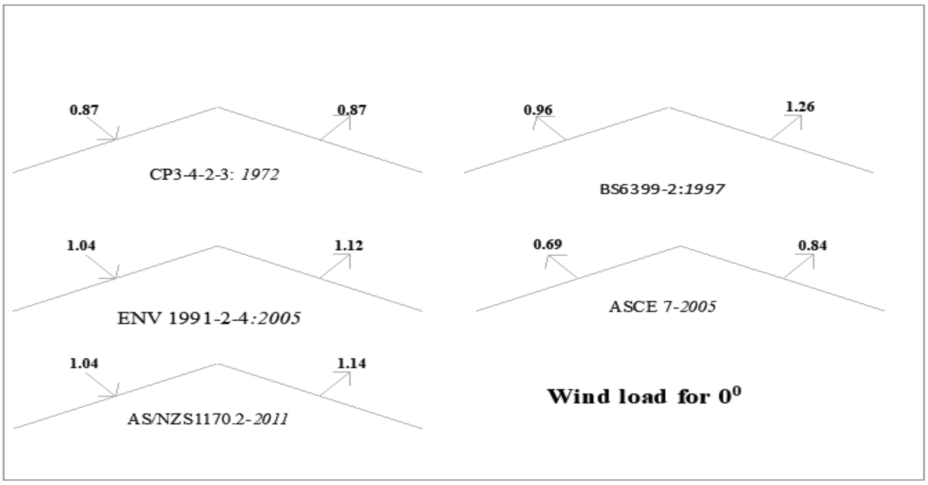

Figure 3. Extreme wind load on portal roof.

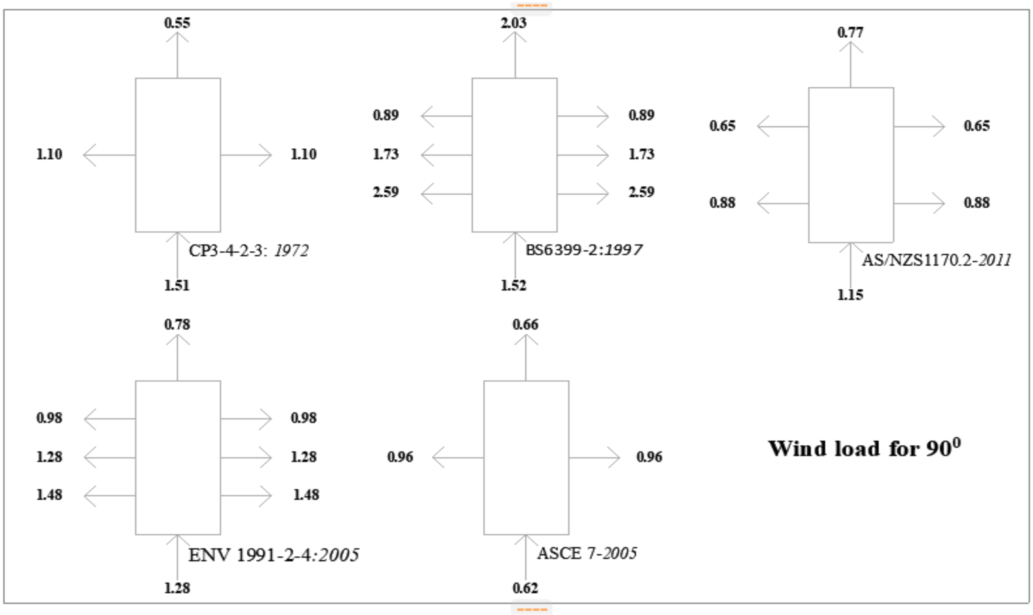

Figure 4. Extreme wind load on ten story building.

4. Discussion

The basic premise is that wind loading phenomena is invariant and wind loads derived for a given reference wind speed should be the same across all the wind load standards. Across the five standards it was clear that wind load equation followed a model of some sort where wind load was equal to the product of the dynamic velocity pressure and the aerodynamic coefficients where the dynamic velocity pressure accounted for factors of the wind speeds that have been modified by the topography, terrain and altitude whereas the aerodynamic pressure accounted for the building characteristics; shape, size and number of openings, guest effect factors internal and exposure factors as summarized in table 5.

Wind load =Dynamic Pressure(q) × Coefficients(C).

$$P = q \times C$$ **Equation 2**

Total pressure mainly depends on three factors namely, the wind speed, external and internal pressure coefficients. The five standards adopted reference wind speeds with different averaging time with recurrence interval of 50years. Across the five standards it is clear that the reference wind speed is dependent on terrain roughness and height above ground. The five standards use reference wind speeds that are related to a height of 10 meters above the ground. The different definition of the reference wind speed accounts for significant differences in the wind load. Conversion of these wind speeds to respective dynamic velocity pressure by terrain and topographic coefficients also leads to differences in the final wind load.

External and internal pressure coefficients are different from one code to another due to their different methods and strategies of determination of these coefficients in relation to their existing climatic conditions. A quantitative comparison has been presented in table 10 for both building. Since most of the parameters had been normalized in the case study and variation does appear to be large, the only reasonable explanation would be that different standards have adopted different wind tunnel test results on which the coefficients have been based.

Other coefficients include the internal and external pressures, exposure factor, shape factor or aerodynamic factor, guest effect factors and the dynamic response of the building. These factors are specific to individual standard according to the prevailing conditions in the native country and the different strategies adopted in determination of these coefficients. The ASCE and AS/NWZ both specified for an importance factor while the other three standards are silent in this regard. A unique importance factor is associated with buildings or structures of a certain category.

For the case study to check for correlation of the wind loading standards coefficient of variation was computed for the extreme wind load cases that were presented in figure 4.1 and figure 4.2. It was evident that for the portal frame structure the coefficient of variation of total wind load ranges from 15% to 18% while for the ten-story building the coefficient of variation of total wind load ranged from 30% to 64%. It is also clear that as the height of the building increases, the coefficient of variation also increases with the highest range being in the leeward wind direction of the ten-story building.

5. Conclusion

This research examined the differences and similarities in wind load analysis on a low-rise building of five major international wind standards. The aim was not only to identify the role of various parameters that contribute to variations in the overall analysis but also compare the induced loads on two structures in the along-wind and across-wind directions. The findings of this research were in broad agreement with the results from other research. The following conclusions were therefore deduced.

1. The varying definitions of wind characteristics including mean wind velocity profiles, gust effects and wind correlation coefficients are the primary contributors to the variations in the predicted wind load.
2. Parameters associated with the wind velocity characteristics contribute the most towards apparent differences in the resulting wind responses in both the along-wind and across-wind.
3. (BS6399-2:1997) predicts a higher loading in the leeward direction for the portal frame warehouse greater than 20% compared to the other standards and 85% in for the ten-story building sidewall while (ENV1991-2-4_2005) gives a higher loading for portal frame warehouse in the windward direction greater than 13% compared to the other standards.

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