Variability of Time Independent Wind Load Components

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ABSTRACT: This paper investigates the variability of the primary time independent components of the design wind load formulation. It is shown that the variability of these components has a significant influence on the total reliability of wind loads. The use of comparative studies of international wind load standards as an indicator of the variability of the time independent wind load components is discussed. A two part comparative study is done to determine the variability. It is found that the existing representative probability model of wind load components underestimates even a lower limit estimate of the variability of these components, particularly for pressure coefficients. Furthermore, insight is gained into the effects of various structural and wind load parameters on the total variability of wind loads.

1. INTRODUCTION

Wind is an intrinsically uncertain natural phenomenon. This uncertainty is a critical aspect of wind actions as structural loads that can only be treated probabilistically. This investigation is part of an ongoing project to develop new wind load probability models for the South African environment. This paper discusses a critical step this process, namely, determining the variability of the time independent wind load components of the design wind load formulation.

2. PROBABILISTIC MODELING OF WIND LOADS

The design wind load formulation is used to represent the combination of multiple physical processes which result in wind pressures acting on a structure. As with any physical process, each of these processes is subject to uncertainties. These uncertainties need to be quantified and taken into account in the calibration of the wind load formulation in order to achieve a desired level of reliability.

Probabilistic models describe the uncertainty of the design wind load through the use of representative probability distributions of the wind load components. These distributions are defined by three parameters: distribution type, mean value and coefficient of variation. The parameters determine how the probability models describe the total uncertainty of the wind load, therefore it is imperative that each one be determined using the best available reliability sources.

The general formulation of design wind loads is given in Equation 1. The variables are defined in Table 1, along with the representative statistical parameters of the distributions used to describe each component. These parameters are normalized with respect to their characteristic values. It should be noted that there are numerous levels of approximation which may be considered when determining wind loads on structures. Many formulations take account of factors such as wind directionality and dynamic effects. Furthermore, most probabilistic models also include a model uncertainty factor

Table 1: Wind load formulation variables and representative distribution parameters.

Symbol	Variable	Distribution Type	Systematic Bias	Coefficient of Variation
Q_{Ref}	Annual extreme pressure	Gumbel	1.10	0.18
c_r	Terrain roughness	Normal	0.80	0.10
c_a	Pressure coefficient	Normal	1.00	0.10
c_g	Gust factor	Normal	1.00	0.10

when used for reliability calibration. For the purposes of this investigation, however, only the fundamental formulation of design wind loads as given below was considered.

$$Q = Q_{Ref}\, c_r\, c_a\, c_g \tag{1}$$

The representative probability model of the design wind load formulation given in Table 1 was adopted from JCSS (2001) and was used in the calibration of the Eurocode 1 wind load stipulations by Gulvanessian and Holický (2005). However, the reliability basis used for the development of the JCSS model is unclear. This serves as the primary motivation for the ongoing project to develop a new wind load probability model for the South African environment based on transparent and reliable data.

The development of a new probability model requires that the statistical parameters of each wind load component be investigated. Research on the variability of the time dependent wind load component in South Africa has been presented by Kruger et al. (2013) and Botha et al. (2014). This paper investigates the variability of the time independent components, specifically pressure coefficients and terrain roughness factors. The investigation is limited to the global reliability of regular structures in order to obtain a generic representation of uncertainty. Uncertainties representative of special conditions such as dynamic effects or special structures should be investigated separately.

2.1. *Time Dependence of Wind Load Components*

The design wind load formulation may broadly be divided into two parts. The first is the description of the free-field wind at the location of the structure, a time dependent process which is subject to the stochastic nature of strong wind conditions. The second is the conversion of the free-field wind into wind pressure loading on the structure. This conversion is a function of the aerodynamic and terrain roughness effects. Where the free-field wind is time dependent, these factors are time independent as the physical conditions which influence them, namely the geometry of the structure and the surrounding terrain, remain relatively constant over time.

Free-field wind is often considered to be the primary source of uncertainty in the wind load process as it forms the basis of wind loads. The time independent components act as magnification or reduction factors of the free-field wind pressure. It is clear that although the aerodynamic factors and terrain roughness factors are theoretically time independent, they are not independent of the free field-wind. These factors do have a significant influence on the total wind load, however, and the uncertainties related to them should not be underestimated.

To illustrate the importance of the time independent wind load components on the reliability of wind loads, specifically the variability of these components, a simple First Order Reliability Method (FORM) comparison was done. The wind load formulation was simplified to the product of two variables, the time dependent free-field wind (D) and the combined time independent wind load components (I). The deterministic design wind pressure (w_d) was varied parametrically. Using a basic limit state function given in Equation 2, FORM analyses were done using two probability models. The first model was derived using the basic distribution parameters from the representative wind load probability model in Table 1. The second model used the same distribution parameters for the time dependent component, but double the value for the coefficient of variation of the time independent components was used. The models used in the FORM comparison are summarized in Table 2. The results showing the design wind pressure plotted against the calculated reliability index values (β) are given in Figure 1.

$$0 = D * I - w_d \tag{2}$$

Table 2: FORM comparison probability models

Symbol	Type	Model 1		Model 2	
		Bias	CoV	Bias	CoV
D	Gumbel	1.10	0.18	1.10	0.18
I	Normal	0.80	0.14	0.80	0.28

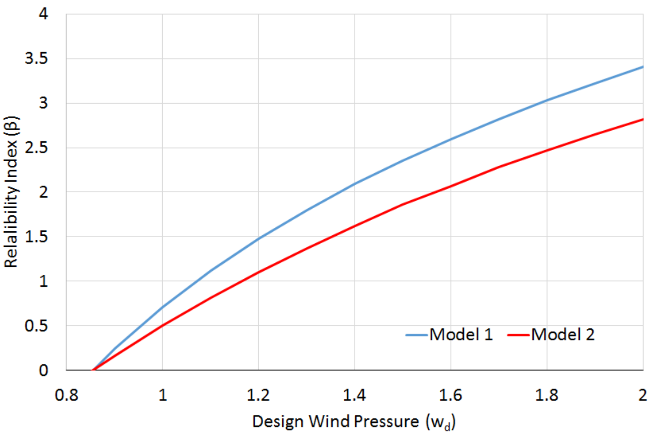

Figure 1: FORM comparison results.

The results clearly indicate that the variability of the time independent components markedly affects the total reliability of the design wind load. Although doubling the variability assumed by the representative probability may seem extreme, this paper will show that the coefficient of variation used in the second model is a reasonable approximation of the total variability of the combined time independent wind load components.

2.2. *Wind Load Uncertainty Characterization and Reliability Basis*

In addition to differentiating the wind load components based on their time dependence, the components are also characterized by different types of uncertainties. Much research has been done in the field of extreme wind prediction. Through the continuous process of gaining additional data and improving probability models, the systematic uncertainties related to the description of the free-field wind are reduced and the aleatoric uncertainties inherent in strong wind conditions become dominant. Aerodynamic and terrain roughness effects, on the other hand, are dominated by epistemic uncertainties due to the simplicity of the models which are used to describe them.

As the variability of the time independent components is due to epistemic uncertainties, a reliability investigation of these components needs to be based on information which reflects the systematic uncertainties. Arguably the most important part of any reliability investigation is obtaining reliable information and data. This is particularly challenging when considering pressure coefficients and terrain roughness factors due to the scope of the design situations which may be considered for even the most basic structures. This investigation explored and assessed the use of the comparison of wind load standards as an indicator of the variability of the wind load components considered.

Wind load standards may be characterized by a two-step development process. Firstly, background information and research is converted into operational models to describe design wind loads. These models are then modified and adapted into practical design procedures which systematically cover the required design situations. The background operational models are the true source of the epistemic uncertainties, and the comparison of those models would provide the closest approximation of the variability. However, without clear background documentation detailing the development of the standards, as is often the case, these models are not readily accessible. The wind load standards themselves are accessible, and the standards may serve as a valuable source of information to compare the differences between the theoretical models and data.

Using the comparison of standards has clear drawbacks. Foremost among these is the fact that one cannot use the wind load standard stipulations as statistical data. As stated above, the basic data used in the development of the standards may have been modified to develop the final design procedures. This process may result in additional levels of conservatism being added or simplification of the background models. Furthermore, there are significant differences in the formulations of the various standards, such as pressure zone area definitions, pressure coefficients for different roof slope intervals and terrain roughness factor cutoff heights. As a result, the comparison of standards may lead to additional variability being observed. Careful filtering out of the differences due to format can ensure that the differences in standard generated values will reflect the differences in the background models used in their development and may serve as an indication of the true variability.

This may be achieved through a comprehensive comparative study in which the sources of additional variability are identified and treated appropriately. This process should consist of the following steps:

1. A design situation is defined and the corresponding codified parameters from selected wind load standards are determined. These codified values provide an estimation of the mean characteristic value of the respective parameters for the specific situation.
2. The scatter of the codified parameter values around the mean for the design situation is used to estimate the epistemic variability of the parameters for the given situation.
3. The design situation is changed parametrically and the first two steps repeated. The trends which arise in both the characteristic values and the variability may then be identified as more situations are considered.
4. By repeating the process within an acceptable sample space of design situations, a estimation may be made of the representative variability of the time independent wind load components.

Assuming that each wind load standards is an independent sample and represents a unique formulation which integrates data from different sources, comparison of standards provides a reasonable approximation of the variability of the time independent wind load components. This method underestimates the true variability where different standards are based on the same models. The variability is underestimated further due to the nature of epistemic uncertainties as not all sources of uncertainty are considered. It is therefore apparent that the methods presented in this paper provide a lower bound approximation of the true variability of the time invariant wind load components.

3. METHODOLOGY

Seven international standards were considered in this investigation, namely SANS 10160-3 (2011), EN 1991-1-4 (2005), BS NA EN 1991-1-4 (2010), AS-NZS 1170-2 (2011), ISO 4353 (2009), ASCE 7 (2010) and NBC (2010). The SANS wind load stipulations are based on EN 1991, which provides a comprehensive and detailed wind load formulation. BS NA EN 1991 is a National Annex to EN 1991 which provides different parameters for the same general formulation. Similarly, the AS/NZS, ISO and ASCE wind load stipulations follow a single formulation, but each standard provides different parameters within the overarching formulation. This formulation is slightly less detailed than the EN formulation, but is easily applied to a large scope of design situations. Finally, the NBC stipulations for primary wind loads on structures provides yet another formulation. ASCE also includes stipulations for the NBC formulation, but these were not considered in this investigation.

A comparative study of wind load standards was done to investigate the variability of time independent components. The study was done in two parts. In the first part the pressure coefficients and the terrain roughness factors provided in the wind load standards were compared individually in order to determine the variability of each component independently. The second part investigated the combined effects of the time independent wind load components. Instead of comparing individual pressure coefficients or terrain roughness factors, a parameter study was done on representative structures and the design wind pressures as calculated according to the stipulations given by each of the standards were compared. Constant values were chosen for the time dependent component of the wind load across all parameter studies to ensure that the observed variability was solely due to the time independent components.

A critical part of the comparative study is the selection of the sample space. The sample space must be chosen in such a way that it provides the best reflection of the pure epistemic uncertainties and excludes special cases and outliers which may skew the results. The scope of this investigation is limited to structures representative of buildings commonly designed in practice. The parameter ranges selected in this paper were based on engineering judgement, but the investigation may be refined in future through a comprehensive study to determine the optimal sample space.

4. INDIVIDUAL COMPONENT INVESTIGATIONS

4.1. *Pressure Coefficients*

As pressure coefficients are presented and implemented in various ways, the parameter range was chosen so that the values obtained from the different standards would be comparable. The external pressure coefficients on walls, mono-pitched and duo-pitched roofs were compared. Comparisons were done for roof pitch values between 0° to 20°. Furthermore, as the global reliability of structures was under investigation, only large area-averaged pressure coefficients were considered.

Critical positions on the structures were defined and the pressure coefficients specified by each wind load standard at those positions were recorded. The pressure coefficients were normalized with respect to the average value of each position, allowing direct comparison of the pressure coefficients at all positions. The coefficients of variation were then determined for each structural component as well as across all observation positions. The results are presented in Table 3.

4.2. *Terrain Roughness Factors*

A similar procedure to that used to determine the variability of pressure coefficients was used. Three representative exposure categories corresponding to sea, open country and suburban terrains were selected from Eurocode. The roughness lengths used are given in Table 4. The equivalent roughness factor profile for each representative exposure category was then calculated using the stipulations of the wind load standards. The profiles were sampled at 1 m intervals. The roughness factors at each height were normalized with respect to the calculated average roughness factor at that height, allowing direct comparison of the roughness factors across the entire height. The results of the investigation are presented in Table 5.

4.3. *Combined Variability*

By assuming that both the pressure coefficient and terrain roughness uncertainties are best described by a Normal distribution, as is the case in the representative probability model, the total variability of the two components may be calculated. This allows for a single coefficient of variation of the combined components which may then directly com-

Table 3: Coefficients of variation of pressure coefficients.

Component	Coefficient of Variation
Walls	0.27
Flat Roof	0.28
Mono Pitched Roof	0.30
Duo Pitched Roof	0.27
Total	0.33

Table 4: Representative exposure categories used in comparative study.

Category	Description	Roughness Length
1	Sea	0.02 m
2	Open Country	0.05 m
3	Suburban	0.40 m

Table 5: Coefficients of variation of terrain roughness factors.

Exposure Category	Coefficient of Variation
1	0.11
2	0.10
3	0.12
All	0.11

pared to the coefficient of variation obtained from the combined component investigation to follow. A combined coefficient of variation of 0.35 was calculated.

5. COMBINED COMPONENT INVESTIGATION

5.1. Parameter Study Methodology

A comprehensive comparative study of the various design wind load standards requires a large number of comparisons covering a wide range of representative design situations. This was achieved through a parameter study of the design wind load formulation rather than using individual comparisons of various reference structures. This provided an indication of the variability of the time independent wind load components as well as insight into which aspects of the structure's geometry have the most significant impact on the variability of the wind loading process. Furthermore, a parameter study allowed identification of the trends of the additional variation due to the differences in the development of the standards.

To this end, a program was written to automate the process. Every wind load standard considered in this investigation was studied extensively and a separate module was developed for each, which allowed automatic calculation and comparison of different design wind loads. The program calculated wind loads based on seven primary parameters:

- **Structure Type:** The structure could be defined as a mono- or duo-pitch building.
- **Wind Direction:** The program allowed for three orthogonal wind directions. 0° defined a wind direction perpendicular to the ridge of the structure blowing onto the low eave, 90° running parallel to the ridge of the structure, and 180° perpendicular to the ridge of the structure blowing onto the high eave.
- **Exposure Category (EC):** The three representative exposure categories as used in the individual component investigations were used in the program.
- **Structure Width (W):** Defined as the horizontal dimension perpendicular to the ridge of the structure.
- **Structure Length (L):** Defined as the horizontal dimension parallel to the ridge of the structure.
- **Wall Height (H):** Measured from ground level to the lowest eave of the building.
- **Roof Pitch (α):** For structures with a roof pitch of less than 5°, the roof was assumed to be flat and the flat roof procedures for calculating wind pressures were followed.

Table 6: Reference structures and parameter ranges. Smaller reference structure parameters given in parentheses where applicable.

Structural Parameter:	Parameter Ranges Reference	 Lower	 Upper
α:	10°	0°	20°
H:	5m	5m	35m (25m)
W:	25m (15m)	10 m	40m (30m)
L:	50m (30m)	10 m	70m (50m)
EC:	2	1	3

Once these parameters were defined the external design wind pressure distributions on the structure were calculated. As with the individual component investigation, only wind pressures resulting in primary structural actions were considered, i.e. cladding and component pressures were not considered. The pressure was then integrated over each face of the structure and a spatially averaged wind pressure value was recorded per face. The coefficient of variation of the design wind loads could be determined for each face and across the structure as a whole.

The parameter study needed to be done in such a way that it allowed investigation of a wide range of design situations as well as effective analysis and comparison of the results. In order to accomplish this, a reference structure was defined and each of the parameters were varied in turn within selected parameter ranges. This procedure was done for two reference structures. The reference structural parameters and parameter ranges used in each parameter study are given in Table 6.

Five combinations of the two structure types and three wind directions were used in each parameter study and their results recorded separately. As the results for duo-pitch roofs are the same for 0° and 180°, the logical sixth combination was ignored.

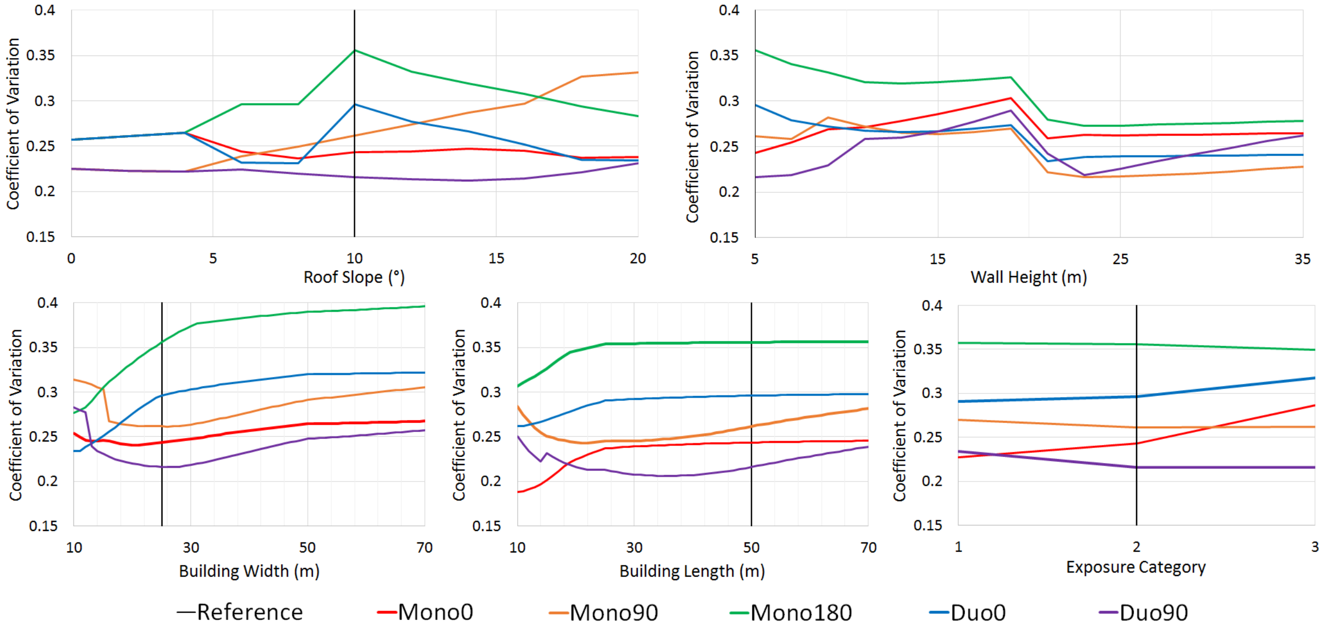

Figure 2: Coefficients of variation plotted against varied parameters for the larger reference structure.

Table 7: Maximum, average and minimum coefficient of variation for all parameter studies. Values in parentheses calculated excluding the "Mono180" case results.

Varied Parameter:	Larger Reference Structure			Smaller Reference Structure		
	Maximum	Average	Minimum	Maximum	Average	Minimum
Roof Slope:	0.36 (0.33)	0.26 (0.25)	0.21 (0.21)	0.30 (0.30)	0.25 (0.24)	0.20 (0.20)
Wall Height:	0.36 (0.30)	0.26 (0.25)	0.22 (0.22)	0.32 (0.32)	0.26 (0.27)	0.19 (0.19)
Width:	0.38 (0.31)	0.28 (0.26)	0.22 (0.22)	0.30 (0.30)	0.24 (0.24)	0.19 (0.19)
Length:	0.36 (0.30)	0.27 (0.25)	0.19 (0.19)	0.31 (0.30)	0.25 (0.24)	0.18 (0.18)
Exposure Category:	0.36 (0.32)	0.28 (0.26)	0.22 (0.22)	0.31 (0.29)	0.25 (0.24)	0.19 (0.19)

5.2. *Parameter Study Results*

Figure 2 shows the results of the parameter study using the larger reference structure. The coefficients of variation are plotted against each varied parameter for the five structure-direction combinations. The vertical black line on the graphs indicates the reference structure. The range of results obtained for both parameter studies is summarized in Table 7. The peak values obtained from the parameter study using the larger reference structure are up to 26.7% higher than those obtained from the second parameter study, but the average values obtained from the two studies only differ by 7.6%.

It may be seen from Figure 2 that there are significant differences between the values obtained for each structure-direction combination. It is clear that for the larger reference structure "Mono180" is the dominant case as it consistently yields the greatest variability. By recalculating the values and excluding the "Mono180" results, as given by the parenthesized values in Table 7, it is shown that although the calculated maximum values are significantly lower, the average values change by less than 6.0% for the larger reference structure. Furthermore, less than 3.8% change is observed in the results of the parameter study on the smaller reference structure, indicating that "Mono180" is not the dominant case for that design situation. This reinforces the use of a comprehensive parameter study across multiple design situations as a valid indication of the variability as extreme cases have little effect on the final calculated average values.

Of the varied parameters, the roof slope study shows the most erratic results, indicating that it has the greatest effect on the variability of the wind loads, second only to the differences in variability between the structure-direction combinations. The wall height parameter study shows erratic results for low wall heights, but the values become stable after a wall height of 20 m is reached. The building width, building height and exposure category parameter studies show relatively consistent variability, indicating that these parameters do not impact the variability of wind loads significantly.

6. CONCLUSIONS

- The variability of the time independent wind load components has a significant effect on the total reliability of wind loads.
- This variability is primarily due to epistemic uncertainties in the wind load formulation.
- The comparison of wind load standards may be used as an indicator of the variability of the time independent wind load components.
- The sampling space chosen in this investigation is based on engineering judgement. The investigation may be refined in future by determining the optimal parameter ranges for unbiased sampling.
- Average coefficients of variation of 0.33 for pressure coefficients and 0.11 for terrain roughness factors were obtained from the individual component investigations. A coefficient of variation of 0.35 was calculated for the combined effect of both components.
- The combined component investigation resulted in average coefficients of variation between 0.24 and 0.28 for total variability of the time independent wind load components.
- The results for the variability of the time independent components of the wind load formulation obtained from this investigation are consistently greater than the variability accounted for by existing probabilistic wind load models, particularly for pressure coefficients.
- Wind direction and roof type have the largest influence on the variability of wind loads. Of the structural parameters, the roof slope has the greatest on the variability, whereas changes in the plan dimensions of the structure have little effect on the total variability.

7. REFERENCES

AS-NZS 1170-2 (2011). "Structural design actions - Part 2: Wind actions." Standards Australia Limited/Standards New Zealand.

ASCE 7 (2010). "Minimum Design Loads for Buildings and Other Structures." American Society of Civil Engineers.

Botha, J., Retief, J., Holický, M., and Viljoen, C. (2014). "Development of probabilistic wind load model for South Africa." *Proceedings of the Thirteenth Conference of the Italian Association for Wind Engineering*.

BS NA EN 1991-1-4 (2010). "UK National Annex to Eurocode 1: Actions on structures, Part 1-4: General actions - Wind actions." British Standards Institute.

EN 1991-1-4 (2005). "Eurocode 1: Actions on structures, Part 1-4: General actions - Wind actions." CEN Brussels.

Gulvanessian, H. and Holický, M. (2005). "Eurocodes: using reliability analysis to combine action effects." *Proceedings of the ICE - Structures and Buildings*, 158, 243 – 252.

ISO 4353 (2009). "Wind actions on structrues." International Organization for Standardization.

JCSS (2001). "Joint Committee on Structural Safety Probabilistic Model Code, Parts 1 to 4.

Kruger, A., Retief, J., and Goliger, A. (2013). "Strong winds in South Africa." *Journal of the South African Institution of Civil Engineering*, 55(2).

NBC (2010). "National Building Code of Canada - Structural Commentaries." American Society of Civil Engineers.

SANS 10160-3 (2011). "Basis of structural design and actions for buildings and industrial structures, Part 3: Wind actions." South African Bureau of Standards.