Structural Safety 57 (2015) 8–17

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

# Synthesis of wind tunnel and climatological data for estimating design wind effects: A copula based approach

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ARTICLE INFO

*Article history:*
Received 16 October 2014
Received in revised form 30 June 2015
Accepted 2 July 2015
Available online 18 July 2015

*Keywords:*
Directionality
Tall building
Copula
Aerodynamic data
Climatological data

ABSTRACT

Accurate estimation of design wind effects on tall buildings is critical to ensure adequate margin of safety against lateral wind loads with a reasonable cost. Design wind effects on tall buildings are estimated by combining aerodynamic data obtained from wind tunnel tests with the climatological or wind speed data of the construction site. Though it is widely agreed that the aerodynamic data obtained from wind tunnel tests is fairly reliable, the various approaches used to synthesize aerodynamic and climatological data are often argued to have shortcomings. For instance, the uncertainty in modeling the correlation effect between sectorial responses has always been a challenge in the sector-by-sector synthesis approach. This paper presents a new copula based approach for modeling this correlation effect between sectorial responses. In addition, the proposed approach is used to assess the uncertainties in assuming sectorial responses to be perfectly dependent or independent while using the sector-by-sector approach. Results of the study showed that a copula based approach can be used for accurate modeling of the correlation effect between sectorial responses. It was also noted that assuming sectorial responses to be perfectly dependent or independent could result in underestimation or overestimation of design wind effects respectively.

## 1. Introduction

Wind-induced responses of tall buildings are often direction dependent because of the asymmetrical nature of their geometrical and/or structural properties. Hence, wind tunnel tests on tall buildings are often conducted for multiple wind directions by rotating the building model with respect to a unidirectional wind flow in the tunnel. The aerodynamic responses measured in the wind tunnel are normalized by the product of a reference dynamic pressure and a certain weighting factor computed based on the type of response. Full-scale design wind effects of the required mean recurrence interval (MRI) can then be estimated by integrating the normalized aerodynamic data with the actual wind speed data obtained from the construction site. Besides the aerodynamic data collected from wind tunnel tests, magnitude of the actual wind speed in a given area also shows variation with direction depending on the exposure and climatology of the area. Hence, synthesis of the aerodynamic and climatological data involves considering this wind directionality effect. The wind directionality effect plays a significant role particularly in the design of wind sensitive structures such as tall buildings. It is agreed among many researchers that neglecting wind directionality effect for wind sensitive structures could result in overly conservative design [1–3]. It was also noted in the works of various researchers [4,5] that significant under estimation of design wind effects could result when the wind directionality effect is not properly considered. Thus, for a safe and economical design it is highly recommended that the wind directionality effect is properly considered while synthesizing aerodynamic and climatological data. Several techniques have been suggested over the years for integrating climatological data into the wind tunnel test results and some of these techniques are briefly reviewed as follows. The first and most simplified approach is the *directionality factor* approach which has been implemented in several design codes and standards. In this approach a single wind speed vector is constructed which consists of the largest wind speed in a given epoch irrespective of wind direction. Similarly, the largest peak aerodynamic coefficient out of all wind directions tested in the wind tunnel is extracted. The wind speed vector is combined with the largest aerodynamic coefficient to estimate the required design wind effect. However, the probability of the largest magnitude wind speed coming in the most aerodynamically unfavorable direction is most likely to be less than 1. In order to account for this reduced probability, some

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http://dx.doi.org/10.1016/j.strusafe.2015.07.004
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design codes and standards recommend using a directionality factor of less than 1. For instance, ASCE 7–10 recommends a directionality factor of 0.85 to be used for most structures including tall buildings. Some researchers showed that the use of such generic reduction factors may not always give a safe result [6,7]. *Upcrossing* method is another synthesis technique used to integrate aerodynamic and climatological data. This method was originally suggested by Davenport [8] and later modified by Lepage and Irwin [9]. The basic concept behind the method lies in estimating the mean upcrossing rate of a response boundary by a wind speed, the inverse of which gives the return period corresponding to the given wind effect. The response boundary is a curve which shows variation of the wind speed required to cause a given level of wind effect as a function of wind direction. Further discussion on the formulation of this approach can be referred from [10]. This method is analytically more involved compared to the other approaches reviewed here. In addition, some researchers [5,11] cited the challenges in accurately evaluating some of the parameters defined in the formulation of this approach. *Storm passage* approach is another technique used to integrate aerodynamic and wind climate data. In this approach, the aerodynamic data obtained from wind tunnel testing is converted into time history of wind effects using hourly recorded directional wind speed data. The time history data is then divided into sub-intervals and extreme value analysis is carried out on the maximum values of the sub-intervals to estimate the required level of design wind effect. Further discussion on the formulation of this approach can be referred from [10,12]. This method is simple to implement provided sufficiently long and reliable wind speed records are available. In addition, it involves fewer approximations in its formulation compared to the upcrossing method. However, this method is computationally intensive as it involves evaluating hour by hour time history of wind effects. Sufficiently long and reliable wind speed data for every project location may not be readily available as well. *Sector-by-sector* approach is another method used to synthesize aerodynamic and climatological data. In this approach, the wind speed and aerodynamic data are grouped and synthesized in sectors to get extreme wind effects corresponding to each sector. The final design wind effect will be estimated considering the statistical correlation between the sectorial wind effects. However, proper modeling of this correlation effect between sectorial wind effects has always been a challenge in applying this method. Compared to the upcrossing and storm passage approaches, this method is simple and computationally less intensive. Considering this advantage, this method can be more appealing if the statistical correlation effect between sectorial wind effects can be evaluated more accurately. This paper introduces a new copula based approach for modeling this correlation effect between sectorial wind effects. Formulation of the method will be discussed in detail in the following section followed by a numerical example illustrating its application. In addition, the method will be used to assess the uncertainties in the traditional simplifying assumptions of perfectly dependent and independent sectorial wind effects while implementing the sector-by-sector approach.

## 2. Sector-by-sector directional analysis

In the sector-by-sector synthesis approach the aerodynamic and directional wind speed data are grouped in sectors. Grouping of the data in sectors is required since the wind speed data is often available for limited number of directions compared to the aerodynamic data measured in the wind tunnel. For instance, the aerodynamic data is often available for 36 directions whereas the actual wind speed data might be available only for 8 or 16 directions. Thus, the decision on the number of sectors to be used is mostly dictated by the available directional wind speed data. The largest magnitude peak aerodynamic coefficient in each sector is combined with the corresponding sectorial wind speed to get the largest sectorial wind-induced response as follows:

$$\hat{R}_i = \frac{1}{2}\rho_a W_R \times \hat{C}_{Ri} U_i^2 \tag{1}$$

where $\hat{R}_i$ is a vector of peak wind-induced response corresponding to sector $i$; $\rho_a$ is the density of air; $W_R$ is a weighting factor computed based on the type of response; $\hat{C}_{Ri}$ is the largest peak aerodynamic response coefficient in sector $i$ and $U_i$ is a vector of extreme wind speed corresponding to sector $i$. Extreme value analysis is then carried out to estimate response of the required MRI, say $T$ years, corresponding to sector $i$. If there are $k$ sectors, extreme value analysis is carried out for each sector separately and a total of $k$ sectorial extreme wind-induced responses will be obtained. The question one might ask at this stage would be whether it is possible to take the largest sectorial response ($R_{max}$) as the design response of $T$ years MRI or not. In probability terms, this is the same as asking if the probability of non-exceedance of the response $R_{max}$ in $T$ years is given by $Pr(R \leqslant R_{max}) = 1\text{–}1/T$. The non-exceedance probability $Pr(R \leqslant R_{max})$ can be computed from the joint distribution of sectorial responses which is given as follows:

$$Pr(R \leqslant R_{max}) = Pr[(R \leqslant R_{max})_1, (R \leqslant R_{max})_2, \ldots, (R \leqslant R_{max})_k] \tag{2}$$

where the subscripts 1,2,. . .,$k$ denote sector numbers. If all the sectorial responses are fully correlated (perfectly dependent) the multivariate distribution given in Eq. (2) can be evaluated as:

$$Pr(R \leqslant R_{max})_{dep} = min[Pr(R \leqslant R_{max})_1, Pr(R \leqslant R_{max})_2, \ldots, Pr(R \leqslant R_{max})_k] \tag{3}$$

where the subscript *dep* shows the condition of full dependence between sectorial responses and the operation min[] denotes the minimum value. Since the minimum probability of non-exceedance which is $1\text{–}1/T$ is obtained in the sector where the largest sectorial response ($R_{max}$) occurs, Eq. (3) can be written as:

$$Pr(R \leqslant R_{max})_{dep} = 1 - 1/T \tag{4}$$

In contrary, if all the sectorial responses are fully uncorrelated (perfectly independent) the multivariate distribution given in Eq. (2) can be evaluated as the product of sectorial probabilities as follows:

$$Pr(R \leqslant R_{max})_{indep} = Pr(R \leqslant R_{max})_1 \times Pr(R \leqslant R_{max})_2 \times \ldots \times Pr(R \leqslant R_{max})_k \tag{5}$$

where the subscript *indep* shows the condition of full independence between sectorial responses. Hence, under this condition the

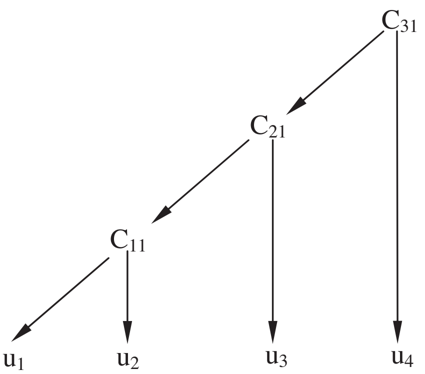

**Fig. 1.** Schematic illustration of the fully nested construction of a multivariate Archimedean copula with four random variables.